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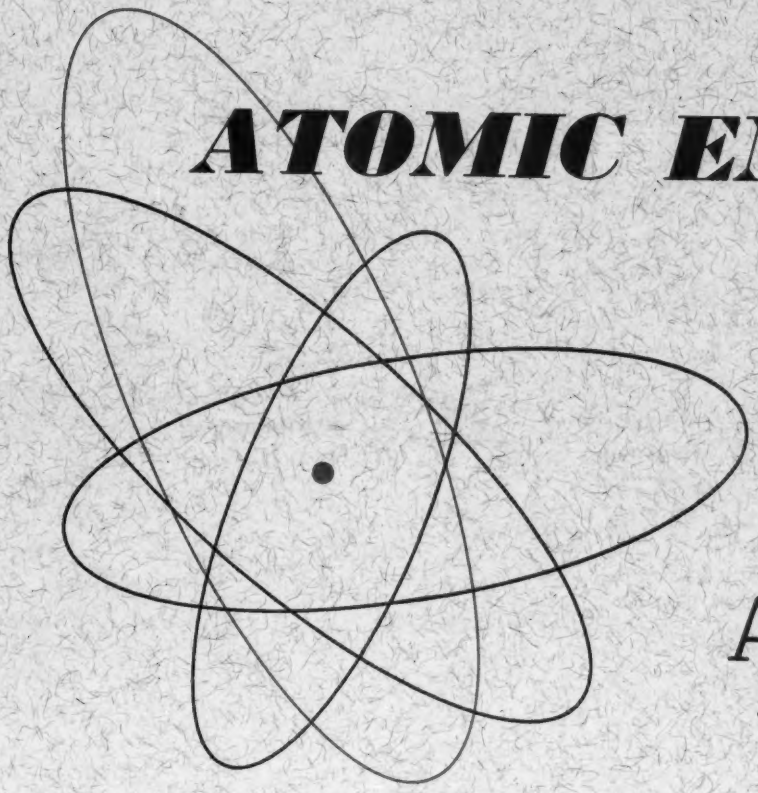
ATOMIC ENERGY



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THE SOVIET JOURNAL OF

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NOTE

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NEW DATA ON THE GEOLOGY AND ECONOMICS OF THE RAW MATERIAL BASIS OF URANIUM IN CAPITALIST COUNTRIES

N. S. Zontov

In recent years, considerable data indicating important changes in the structure of the reserves and production of uranium in capitalist countries, the relative industrial importance of the various genetic types of uranium deposits, and the role of regional geological structures and stratigraphical systems have appeared in foreign literature, particularly in reports presented to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958). These data lead to a new approach to the prospecting of uranium deposits and the development of new prospecting criteria.

Reserves and Production of Crude Uranium

Ores are considered as industrial in such cases where the extraction of uranium from them is profitable at a market price of not more than 26 dollars per kg of uranium in the chemical concentrate. There is a tendency for a reduction in this price to 21 dollars per kg of uranium. At these prices the mining and processing of uranium ores in the USA, Canada, and other countries is considered to be profitable if the ore contains 0.085% uranium. The gold-uranium ores of the Union of South Africa, with a mean content of 0.026% uranium, obtained as a by-product from the sludges after extraction of the gold in the ores form an exception. The cost of South African uranium is equal to the cost of processing the slurries and it can, therefore, compete with American and Canadian uranium although the uranium content in the ore is very low.

In practice, ore containing mainly 0.026-0.30% uranium is mined in capitalist countries (Fig. 1). Ores with a uranium content greater than 0.30% are rare; they are found in the hydrothermal deposits of Shinkolobwe (Belgian Congo) and Port Radium (Canada), where the reserves have, to a considerable extent, already been exhausted, and also in the uranium-bearing sandstones of the Colorado Plateau (USA). Prospecting for new deposits of rich uranium ores has not given positive results.

The vast reserves of uranium contained in the marine shales, phosphate rocks and pyrochlore-bearing granites of the USA and other countries are not worked at present because of their low uranium content (less than 0.03%). Data on the reserves of uranium in industrial ores (converted to metric tons of metallic uranium) mentioned in reports to the Second Geneva Conference and in other literature sources are given in the Table. The distribution of the reserves and output of uranium according to countries is shown in Fig. 2.

The major part of the reserves and production of uranium (about 90%) are concentrated in the USA, Canada, and the Union of South Africa as a result of the discovery and industrial utilization of deposits of new geological types in these countries: uranium-bearing conglomerates in Canada and the Union of South Africa, and Uranium bearing sandstones containing asphaltite in the USA. New mines and processing plants were constructed in these countries, which brought about a fundamental change in the state of the crude uranium industry. Uranium occupied second place among Canadian exports, nickel being the

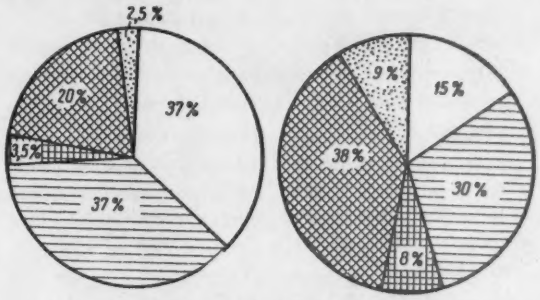
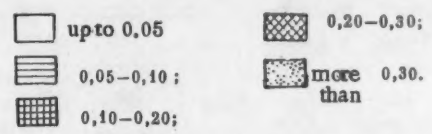


Fig. 1. Distribution of reserves and production of uranium according to its content in the ore: a) reserves; b) output; uranium content in the ore, %:



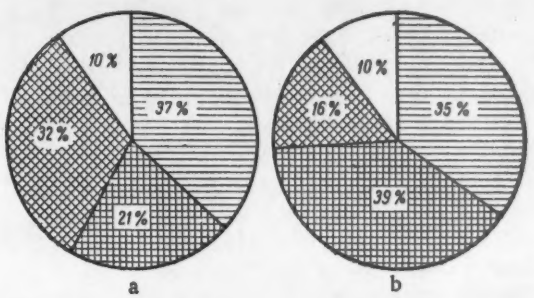


Fig. 2. Distribution of reserves and production of uranium according to countries: a) reserves; b) production.

Reserves and Output of Uranium

Country	Reserves of uranium in 1958, tons	Uranium content in the ore, %	Production of uranium in 1957, tons	Expected level of production of uranium in 1959, tons
Canada	295 000	0,087	5 100	10 000
Union of South Africa	255 000	0,026	4 780	5 400
USA	170 000	0,22	6 500	11 500
Australia	10 100	0,22	380	900
France	15 000	0,15	380	750
Italy	10 900	0,091	5	100
Belgium (Belgian Congo)	6 000	0,30	850	850
Other countries (Spain, Portugal, India, Japan, Argentina, etc.)	38 000	0,10	205	500
Total	800 000	0,053	18 200	30 000

most important export. The value of uranium exports in 1958 was roughly equal to the total value of the exports of lead, zinc, and copper, and greater than the total value of gold, silver, and platinum. In the Union of South Africa in 1957, the profit made by the uranium industry was almost equal to that of the gold mining industry.

In recent years, a number of countries have shown promising results in the prospecting of uranium deposits and the development of the crude uranium industry.

In France, seven deposits of the hydrothermal type are being worked; these are located in the provinces of Limousin, Forez, and Vendée, in which the proved reserves are about 15 thousand tons of uranium in ores containing 0,10-0,18% uranium.

At present, Spain produces only 10 tons of uranium per year, but there is a possibility that the production may be increased to 200 tons per year in the immediate future. Uranium production in Portugal is apparently at the same level as in Spain. Italy has had considerable successes in in uranium prospecting; it is planned to commence uranium production in 1960 and to produce 350 tons of uranium metal per year by the end of 1962.

Several uranium deposits have been found in the Federal German Republic, the most interesting of these being deposits in Permian porphyries on Rhineland-Pfalz and Bavaria, where small mines and processing plants are under construction. In 1958, a plant with an annual output of 10 tons of uranium was put into operation; a plant with a annual output of 150 tons of uranium is under construction in Rhineland-Pfalz.

Sweden has vast reserves of uranium in the form of low-grade bituminous shales containing 0.02-0.03% uranium; 10 tons of uranium per year are obtained from these shales. A new plant which, from 1963, will produce 120 tons of uranium per year and completely satisfy Swedish requirements of this metal is under construction.

Other West European countries (Denmark, Norway, Holland, and Switzerland) are as yet without their own sources of crude uranium, but prospecting work is proceeding satisfactorily.

Of the Asiatic countries, India and Japan have had certain successes in uranium prospecting. In India, together with previously known uranium-bearing monazite sands, hydrothermal deposits have been found in the Singbhum copper belt (Bihar) and in the Precambrian shales of Rajasthan. From previously published data these reserves contain about 12 thousands tons of uranium. 100 tons of uranium had been obtained so far in the thorium plant at Trombee as a by-product of the treatment of monazite sand. A plant for processing the tailings from the copper ore industry in order to extract the uranium is under construction at present in India.

In Japan, an industrial deposit of uranium has been discovered in Neogene conglomerates; prospecting of this deposit confirms the presence of not less than 500 tons of uranium with a content of 0.05% in this ore. A number of hydrothermal deposits here are only in the process of survey operations.

In South America, uranium prospecting is being carried out now in Argentina, Brazil, Chile, Colombia, and other countries. The uranium industry in Argentina is small and is based on deposits of sedimentary rocks of Cretaceous age in the region of Malargüe (Mendoza Province). Prospecting and survey operations are also being carried out in other regions of the country. Uranium ore is processed at three plants in succession to obtain uranium of reactor purity. In 1957, about 30 tons of uranium was produced from ore with a content of 0.50-0.90%. In other countries of South America the production of uranium is in the initial stage.

In Australia, the uranium mines and plants at Radium Hill and Rum Jungle produced 380 tons of uranium up to 1958 in the form of chemical concentrates. After the completion in 1958 of the mine and plant at Mary Kathleen with an annual production of 400 tons of uranium, and the plant with an annual production of 120 tons at the Alligator River deposit in 1959, Australia will have an annual production of about 900 tons of uranium.

In Africa, apart from the Union of South Africa, uranium is produced in the Belgian Congo and in Northern Rhodesia. In the latter, uranium deposits have been discovered in the same copper belt in which the Shinkolobwe deposit is located. Based on these deposits, a mine and plant at Mindoze, near Kitwe, were put into operation in 1957. A little uranium ore is produced in Mozambique; uranium ore is also found in French Equatorial Africa (Gabon) and in the Sudan.

Uranium mineralization has been found in Egypt at several points in Neogene and Cretaceous sedimentary rocks in which drilling is in process.

Economic Importance of the Various Geological Types of Uranium Deposits

Nininger [1, 2] divides all uranium deposits into three types: uranium-bearing conglomerates, sedimentary, and vein (or vein-velated). The latter group includes pegmatitic, skarn, and hydrothermal deposits and it is, therefore, better termed the magmatogenic group.

In 1946, vein hydrothermal deposits represented by the rich ores of the Great Bear Lake (Canada) and Shinkolobwe were the main source of uranium. Reserves of these ores formed 92% of the total uranium reserves. The reserves of deposits in sedimentary rocks of the Colorado Plateau formed only 8%. Uranium-bearing conglomerates were unknown at that time. After 1950, when the gold-bearing conglomerates of the Union of South Africa proved to contain industrial uranium, their importance increased markedly and after the discovery in 1953 of the uranium-bearing conglomerates of Blind River (Canada), the uranium reserves in ores of this type represented, in 1955, 75% of all the reserves of capitalist countries. In 1955 the reserves of uranium in sedimentary rocks (located almost exclusively in the USA) and those in vein deposits formed 15% and 10%, respectively, of all the known uranium reserves at that time. At the present time, as a result of the discovery and successful prospecting of uranium in sedimentary rocks in the USA, there is an appreciable increase in the importance of deposits of this type (in 1958 their reserves formed 25% of the total uranium reserves) and the conglomerate reserves now represent 65%. As before, the vein reserves form 10% of the total.

The distribution of the reserves and the production of uranium according to the geological types of the deposits is shown in Fig. 3.

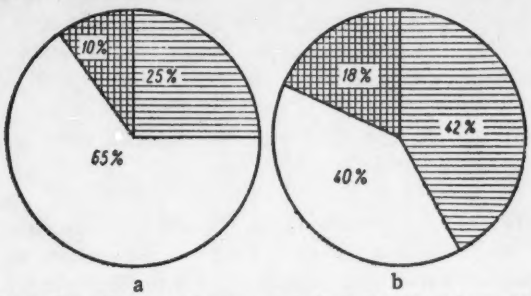


Fig. 3. Distribution of reserves and production of uranium according to geological types of deposits: a) reserves; b) production.

Endogenic deposits;

Deposits in sedimentary rocks;

Deposits.

Magmatogenic Deposits

With the discovery and putting into operation of new deposits of the magmatogenic type, their absolute importance in the uranium industry is continually increasing.

Whereas about 2500 tons of uranium were obtained from these deposits in 1956, by the end of 1959 the production had increased to 7600 tons. But, as a result of the huge increase in the production of ores from sedimentary rocks and conglomerates, the uranium produced from magmatogenic deposits formed only 20% of the total uranium production in 1956, and by 1959 the figure was still the same.

Pegmatitic, sharn, and hydrothermal types are distinguished among the magmatogenic uranium deposits being worked. Figure 4 shows the importance of the various geological types and formations of magmatogenic uranium deposits of capitalist countries.

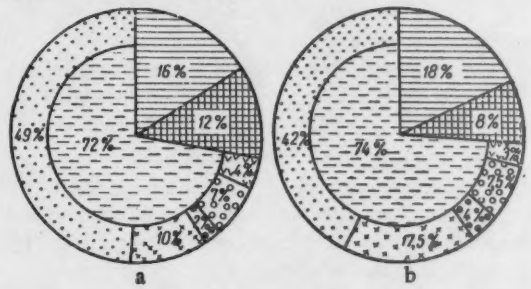


Fig. 4. Distribution of reserves and production of uranium from magmatogenic deposits according to geological types and formations: a) reserves; b) production.

Permatitic deposits;

Skarn deposits

Hydrothermal deposits

Iron-titanium-uranium formation;

Five-metal formation;

Copper-uranium formation;

Nickel-cobalt-uranium formation

Uranium formation proper

Pegmatitic deposits of uranium are very widely distributed, but industrial sources were not discovered among them until recently.

In Canada, the working of uranium deposits in pegmatites of the region of Bancroft (Ontario) commenced in 1957 [3]. The uranium-bearing pegmatites, lying in gneisses and amphibolites of the Grenville series, vary markedly in composition and texture. They rarely have a macrocrystalline pegmatoid texture, characteristic of pegmatitic formations. The principal minerals are microcline, sodic plagioclase, and quartz (in variable amounts), and the usual admixtures (in considerable quantities) are fluorite, calcite, zircon, sphene, pyrite, and pyrrhotine. The uranium is found as irregularly distributed uraninite and uranothorite. The industrial concentrations of uranium minerals are correlated with the intensely crushed sections of pegmatitic dikes. These deposits contain reserves of 8400 tons of uranium (with a content of 0.085%).

A deposit of uranium-thorianite ores in pegmatites is worked in Madagascar where, in 1957, 55 tons of uranium was produced together with thorium.

Skarn deposits of uranium are rare, and the only industrial deposit of this type so far is the Mary Kathleen deposit discovered in 1954. According to the data of Matheson and Searl [4], this deposit is correlated with a zone of development of garnet skarn where relicts of granulites were preserved in places, leading to the formation of skarn. The uranium mineralization appears in the form of a fine dissemination of uraninite generally associated with uranium-bearing orthite , rare-earth minerals, and partially with pyrite, pyrrhotine, and chalcopyrite. The skarn ores are of the uranium-thorium type, the ratio of uranium to thorium being 5:1. The proved reserves of the Mary Kathleen deposit are 5800 tons of uranium in ore containing 0.17% uranium. In Sweden, a uranium deposit in iron ore skarns containing about 0.23% uranium is being prospected; the industrial importance of this deposit has not been established as yet.

Hydrothermal deposits of uranium worked in capitalist countries can be divided into the following formations, in accordance with the association of uranium with other minerals: iron-titanium-uranium, five-metal, copper-uranium, nickel-cobalt-uranium, and uranium proper.

The iron-titanium-uranium formation is represented by the industrial deposit of davidite ores of Radium Hill in South Australia. This deposit consists of several parallel ore beds correlated with the fissures in Precambrian gneisses. The beds contain quartz, black and bronze biotite, ilmenite, and the uranium mineral davidite. Some investigators include this deposit in the pegmatite type, but the majority of geologists consider it to be high-temperature hydrothermal; it has been worked since 1952 and from indirect data contains about 3 thousand tons of uranium.

The five-metal formation also has a restricted distribution among known uranium deposits. The well-known Port Radium deposit is included in this formation. It was the first large source of uranium ores in Canada and played an important part in the development of the Canadian uranium industry. Uranium ores have been mined here since 1933 and are still produced now. The ore beds of Port Radium are correlated with steep tectonic zones in Precambrian sedimentary-volcanic rocks. They are represented either by individual veins with sections rich in ore, or series of veins and veinlets forming stockworks. Apart from uranium, these ores contain nickel and cobalt arsenides, bismuth, native silver, and copper sulfides. The deposit is now worked at a considerable depth, and the output from the deposit is now less than 250 tons per year. The total output of uranium from the Port Radium deposit since working commenced is probably about 10-12 thousand tons. The total proved reserves remaining in the deposit are estimated at 131,200 tons of ore containing 0.50% uranium (or 650 tons of uranium) . It is expected that these reserves will be exhausted by 1960.

The copper-uranium formation is represented by the Rum Jungle deposit, which commenced working in 1954. The uranium deposits are located in the flank of a domal structure of Precambrian sedimentary rocks in layers of carbonaceous shales in the immediate vicinity of a large fault. In association with chalcopyrite, the pitchblende forms a fine metasomatic dissemination in the shales and also a series of fine veinlets located along the stratification. In some deposits copper is absent. In 1958, the proved reserves of the deposit were estimated at 400 thousand tons of ore with a mean content of 2.5% copper and 0.34% uranium (or 1400 tons of uranium). But the deposit has not been prospected in sufficient detail.

The nickel-cobalt-uranium formation is represented by the Shinkolobwe deposit, intense working of which has been carried out since 1923. According to the data of Derrikse and Vaes [5], the Shinkolobwe nickel-cobalt-uranium deposit belongs to the magmatogenic-hydrothermal vein type. The principal metals of industrial importance of this deposit are uranium, cobalt, and nickel. Copper is widely distributed in Shinkolobwe, but in insignificant quantities. The uranium mineralization of the primary ores is represented by crystalline uraninite, together with which are found cobalt sulfides (cattierite) and nickel sulfides (vaesite). In addition, the nickel-cobalt sulfides form independent veins. The rich vein ores of uranium are accompanied by a disseminated mineralization in the country rock; the vein mineralization decreases with depth, and at a depth of 255 m the ores are mainly disseminated.

Shinkolobwe is a large uranium deposit with reserves, according to indirect data, of about 25-30 thousand tons of uranium; a considerable part of the reserves has already been exhausted and the quality of the ores has decreased with an increase in the depth of the workings. This deposit, which in its time played an important part in providing the uranium industry with a rich source of crude uranium, is now only a secondary source (the output is about 850 tons of uranium per year). The remaining reserves are estimated at 5-6 thousand tons of uranium in ore containing 0.30% uranium.

The uranium formation proper occupies the leading place among industrial hydrothermal uranium deposits. It includes numerous deposits of uranium in the region of Beaver Lodge Lake (Canada) and also the deposits of the Massif Central and Armorican Massif in France. The deposits near Beaver Lodge Lake, which have been worked since 1953, are correlated with the fissures and brecciated zones of Precambrian sedimentary-metamorphic rocks, the position of which is controlled by large faults. The ore minerals, represented by a variable amount of pitchblende and hematite together with quartz and calcite, form discontinuous veinlets and a disseminated dispersion. Rich uranium ores are not found here. The deposits of this region are an important source of uranium, providing about 2300 tons of uranium per year. The proved reserves are about 11,800 tons of uranium (the ore contains 0.17% uranium).

The uranium deposits of France form veins or mineralized zones in Hercynian granites. The pitch blende in them is associated with quartz or fluorite.

Vein deposits are also known in the Hercynian granites of Spain and Portugal.

Deposits in Sedimentary Rocks

Industrial deposits of uranium in sedimentary rocks are known in many countries, but the largest of them are located in the Colorado Plateau and its vicinity. Small uranium deposits correlated with continental sandstones, and conglomerates filling the ancient beds of rivers in Triassic, Jurassic, and certain other formations were worked for a long time in the USA. Commencing in 1953, new important deposits were discovered in sedimentary rocks, as a result of which the USA became one of the leading producers of uranium in the capitalist world.

The Shinarump and Chinle formations in Triassic deposits, the Morrison formation in Jurassic deposits, and the Wind River formation in Tertiary deposits are the most important from the industrial aspect; they contain 10%, 67%, and 15%, respectively, of the uranium reserves in the USA, whereas the other sedimentary rocks contain only about 5% of the reserves.

A number of large uranium deposits, including the deposits of Tertiary sandstones of Gas Hills and Crooks Gap in Wyoming and the Jurassic sandstones of Ambrosia Lake in New Mexico, are located in productive or broken oil-bearing and gas-bearing structures or in their immediate vicinity. The Gas Hills and Crooks Gap deposits with reserves of about 25 thousand tons of uranium are located in the flanks of a broken anticline at a distance of about 2 km from discharges of natural gas. Ambrosia Lake, the largest uranium-bearing region in the USA, containing a number of deposits with total reserves of about 100 thousand tons of uranium, is located in a fractured dome from which the oil had migrated leaving solid bitumens behind it.

The association of large deposits of uranium in sedimentary rocks with oil-bearing and gas-bearing structures has attracted the attention of investigators. For example, Russell [6] made an attempt to determine the role of oil and gas in the formation of uranium concentrations. As was shown by investigations carried out by the Colorado School of Mining Investigations, liquid petroleum is a poor solvent and extraction agent for uranium and cannot, therefore, serve as a transport or extraction agent for uranium. The solid pyrobitumens, consisting of solidified oxidized petroleum which is left after the migration of liquid petroleum from a broken trap, play the part of organic resins in an ion-exchange process; they extract the uranium from aqueous solutions and precipitate it, forming uranium-bearing asphaltite. Natural gas can extract and precipitate uranium from solutions if hydrogen sulfide is present in the gas. These theories of the role of petroleum and gas were made the basis of successful uranium prospecting in the regions of Gas Hills and Shirley Basin.

Uranium deposits in sedimentary rocks are also found in certain other countries. In Argentina, for example, industrial uranium ores are correlated with continental sandstones of Cretaceous age. In Italy, large uranium deposits are found in Permian-Triassic continental sandstones in shales of the Maritime and Eastern Alps. Uranium deposits are found in the sedimentary rocks of France: in the Vosges an industrial uranium content has been found in black carboniferous shales (Westphalian stage), in the Massif Central uranium ore occurrences have been discovered in Permian and Tertiary deposits. In Japan, an industrial deposit in Tertiary conglomerates lying on a granite base has also been discovered.

The above data indicate the continually increasing role of uranium deposits in continental sedimentary rocks. The epigenetic origin of uranium, associated with the circulation of undergound water, has been proven for the most closely investigated deposits of the Colorado Plateau. But of late, the hydrothermal theory of Kerr [7] is finding increasing favor.

Uranium Deposits in Precambrian Conglomerates

Uranium deposits in Precambrian conglomerates occupy first place as regards reserves and production of uranium. They are known in Canada and the Union of South Africa. Industrial concentrations of uranium have not been found as yet in the uranium and gold-bearing conglomerates of Jacobina (Brazil). The uranium-bearing conglomerates of Blind River in Canada and Witwatersrand in South Adrica have been described in considerable detail in a number of recently published works. In essence, there are also included in deposits in sedimentary rocks, but they are considered separately because of the development of metamorphic processes in them to a certain degree.

An important feature of uranium mineralizations in conglomerates of Canada and South Africa, of importance for prospecting and extraction, is the correlation of the mineralizations with specific horizons of rocks of a thick stratified sedimentary stratum and the control of the mineralization by sedimentary structures. Structures such as faults, folds, or zones of deformation which control hydrothermal mineralization and are of great importance in the prospecting of hydrothermal deposits, have no influence on the localization and distribution of uranium mineralization in conglomerates.

The uranium-bearing conglomerates of Canada and South Africa differ with regard to the degree of uranium concentration in them and according to their mineral paragenesis. The Canadian conglomerates are characterized by their higher uranium content average 0.085%), the occurrence of uranium as uranite and brannerite, a high thorium content (with a ratio of uranium to thorium of approximately 3 : 1), and a very insignificant

amount of gold; with respect to the association of metals the Blind River deposits are of the uranium-thorium type, in which the thorium may be an industrial component. The Witwatersrand conglomerates are of the gold-uranium type. Their gold content varies from 6 to 25 g/ton; the mean uranium content is 0.026%, traces of thorium are present.

The uranium-bearing conglomerates of the Blind River and Witwatersrand deposits are characterized by the very widespread character, the comparatively uniform distribution of uranium in them, and the simple modes of occurrence; the ores of these deposits are easily worked by ordinary hydrometallurgical methods. All this made prospecting considerably easier, allowed the industrial potential of the conglomerates to be quickly established, and permitted the organization of uranium production on a large scale. These features of uranium-bearing conglomerates are very favorable and promote the search for such deposits in countries where the geological conditions make their occurrence possible.

Distribution of Uranium Reserves According to Regional Geological Structures

Kratchman [8] divides all known uranium deposits into three main geological structures (Precambrian crystalline shields, sedimentary basins, and orogenic zones) and attempts to establish regional structural criteria for uranium prospecting (Fig. 5).

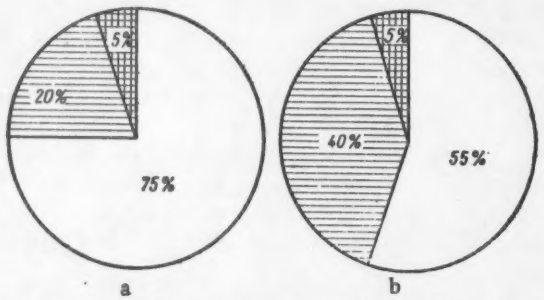


Fig. 5. Distribution of reserves and production of uranium according to regional geological structures: a) reserves; b) production.

Precambrian shields;

Sedimentary basins;

Orogenic zones.

Precambrian shields (Canadian, Australian, and African) include the most important uranium-bearing regions. The deposits in Precambrian shields are included in the pegmatitic, skarn, and hydrothermal types of the magmatogenic class and also in the type of uranium-bearing conglomerates. As indicated by Kratchman and others, the spatial correlation of the uranium deposits to the marginal parts of the shields requires more accurate definition. Magmatogenic uranium deposits are correlated with ancient orogenic ensialic regions; their formation belongs to the late stage of geosynclinical development associated with acid intrusive activity and is controlled by large faults. Deposits of the uranium-bearing conglomerate type are correlated with ancient sedimentary basins at the base of which there are metamorphic rocks and granitic intrusives serving as a source of clastic material and uranium.

Sedimentary basins are the second most important of uranium. They are generally enclosed, which, as noted by Kratchman, is their main characteristic. Such focal basins are favorable for the deposition of uranium and are characterized by the relatively slight thickness of accumulation of terrigenous sediments in a subsiding stable block around which intense folding and faulting take place. Intermontane depressions are included in basins of this type. The Colorado Plateau is a typical example of a focal basin; the Tertiary basins of Wyoming and also the sedimentary basins of the Permian Triassic in North Italy are examples of intermontane depressions.

In spite of considerable prospecting operations carried out in orogenic zones, substantial uranium deposits have not been found in them in any capitalist country. Only France, Spain, and Portugal have industrial uranium deposits correlated with Hercynian folded zones. In the Laramide folded zone of America a few small hydrothermal uranium deposits of different mineral paragenesis have been found .

The Age of Uranium Mineralization

According to Everhart's data [9], endogenic uranium mineralization is included mainly in three metallogenic epochs: the Precambrian, Hercynian, and Laramide-Tertiary.

The Precambrian includes the megmatitic and hydrothermal deposits in the Canadian shield, the Skarn and Hydrothermal deposits in Australia, the deposits of the Belgian Congo and Northern Rhodesia, and the Indian deposits. This metallogenic epoch is the most important in the territory of capitalist countries; it gave rise to the major part of the endogenic deposits, among which there are some of considerable size (Shinklobwe, Great Bear Lake). About 60 % of the uranium reserves of endogenic origin are concentrated in deposits formed in the Precambrian epoch.

The Hercynian metallogenic epoch is the second most important in all capitalist countries and the most important in Europe. It includes the hydrothermal deposits of France, Spain, and Portugal, which contain more than 30% of the uranium reserves of endogenic origin .

The Laramide Cretaceous-Lower Tertiary metallogenic epoch along the west coast of America, which gave rise to numerous and sometimes rich deposits of gold, silver, copper, lead, and zinc, is poor with respect to uranium mineralization. This epoch includes a number of hydrothermal uranium deposits in the western states of the USA, but they form less than 10% of the total reserves of endogenic uranium deposits.

The epochs of accumulation of exogenic concentrations of uranium are more numerous. Uranium con-

centrations of varying amounts are found in the sedimentary rocks of nearly all geological systems, but the edge of the mineralization does not always coincide with the age of the adjoining sedimentary formations. Certain uranium minerals, for example in the Colorado Plateau, are not syngenetic with the adjoining rock and are younger than them. It is, therefore, advantageous to examine the distribution of exogenic uranium mineralization, not according to the epochs of accumulation but according to geological systems containing the mineralization, irrespective of the time of its formation.

The Precambrian system, which includes the very large reserves of uranium ores in the Canadian and South African conglomerates, is a very rich source of uranium. This system contains more than 70% of all the uranium reserves of exogenic deposits. But it must be noted that exogenic mineralization in the Precambrian system has only been found as yet in two regions: Blind River and Witwatersrand.

In many countries, the Lower Paleozoic deposits contain nonindustrial concentrations of uranium but are characterized by large reserves of it. They include the bituminous shales of the Cambrian-Silurian, widely developed in Sweden, and the Devonian and Lower Carboniferous black shales of Chattanooga in the USA.

In some countries the Upper Paleozoic deposits contain industrial uranium deposits. They include the deposits in the Permian sediments of Italy, certain small deposits in the Permian formations of the Colorado Plateau, and the mineralization in the Carboniferous deposits of the Vosges.

The sedimentary formations of Mesozoic systems are far more productive. The Triassic system gives a number of industrial deposits in the Colorado Plateau, where the uranium mineralization is correlated with sandstones and conglomerates of the Shinarump formation. The Jurassic system is the most productive after the Precambrian. The principal uranium reserves in the USA, correlated with the asphaltite-bearing sandstones of the Morrision formation in the Ambrosia Lake region, are concentrated in it. In Argentina are several industrial deposits correlated with sandstones of Cretaceous age.

In certain countries the Tertiary system contains important uranium deposits. The largest of these are the deposits in the Neogene regions of Gas Hills and Crooks Gap; a deposit in the Neogene conglomerates of Japan is known.

SUMMARY

The geological data in the reports to the Second Geneva Conference and in scientific-technical literature allow the conclusion to be drawn that at present the uranium-bearing conglomerates of the Precambrian and the uranium-bearing sandstones containing asphaltite are the main geological types of industrial uranium deposits in capitalist countries; they represent 90% of the reserves and 80% of the production of uranium. Prospecting for deposits of these types naturally attracts the attention of investigators.

Magmatogenic uranium deposits, including pegmatitic, skarn, and hydrothermal types, form only 10% of the reserves and 20% of the output. But in spite of the small proportion represented, the absolute importance of these deposits increasing and in certain countries they are even the principal source of uranium (France, Australia, etc) and the only source of rich ores. In view of this, interest in the prospecting of magmatogenic deposits is not decreasing. The extension of the number of genetic types of magmatogenic uranium deposits as a result of the successes attained in the industrial extraction of pegmatitic and skarn deposits opens up more favorable prospects for the prospecting of new industrial deposits of the magmatogenic type.

Of the regional geological structures, the most productive with respect to uranium are the Precambrian shields; second place is occupied by sedimentary basins of the Paleozoic and Tertiary epoch, and in last place come the folded zones. But in each particular country one of the above-mentioned structures (according to the geological structure of the country) is the most productive; for example, the Precambrian shields in Canada, Australia, and Africa; the sedimentary basins of Mesozoic and Tertiary age in the USA; the Hercynian folded structures in Western Europe. In each country uranium prospecting is, therefore, carried out in accordance with its geological characteristics.

The uranium deposits worked at present are characterized by a uranium content in the ore of generally less than 0.30%. Rich ores with a uranium content of more than 1% which played the decisive role in the first years of development of the uranium industry are now of negligible importance both as regards the absolute output and the proportion of the total output.

As is claimed in [10], as a result of further prospecting operations the known uranium reserves in the industrial deposits of capitalist countries may be doubled. Poor ores with a uranium content of less than 0.03% form a large reserve. With the development and perfection of the technology and an improvement in the economics of the preparation process these ores may become an important source of uranium. Far greater reserves of uranium than those in industrial ores are concentrated in such ores.

LITERATURE CITED

1. R. Nininger, "Geologic distribution of nuclear raw materials," Report No. 862, presented by the USA to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958).
2. Atomnaya Énergiya 5, 668 (1958).*
3. Atomnaya Énergiya 5, 88 (1958).*
4. R. Matheson and R. Searl, Econ. Geol. 51, 528 (1956).
5. J. J. Derriks and J. F. Vaes, Reports to the International Conference on the Peaceful Use of Atomic Energy, Geneva, 1955, Vol. 6, p. 111.

6. R. Russell "Relationship of uranium ore deposits to petroleum and gas-bearing structures," Report No. 774, presented by the USA to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958).
7. P. Kerr, "Criteria of hydrothermal emplacement in plateau uranium strata," Report No. 768, presented by the USA to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958).
8. J. Kratchman, "Regional exploration criteria for uranium," Report No. 1933, presented by the USA to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958).
9. D. Everhart, "Summary of unsolved problems and new trends in uranium geology," Report No. 1932, presented by the USA to the Second International Conference on the Peaceful Use of the Atomic Energy (Geneva, 1958).
10. J. Johnson, "Uranium resources for atomic power," Report No. 1921, presented by the USA to the Second International Conference on the Peaceful Use of Atomic Energy (Geneva, 1958).

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EXPERIMENTAL TEST OF THE BEHAVIOR OF CHARGED PARTICLES IN AN ADIABATIC TRAP

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The present paper is devoted to an investigation of the motion of β particles from tritium in an adiabatic trap. It is shown that under certain conditions the number of reflections of the β particles from regions of high magnetic field (magnetic mirrors) is greater than 10^7. The dependence of the lifetime of the β particle in the trap on gas pressure, magnetic field configuration, and field homogeneity is determined.

An important characteristic of an adiabatic trap is the lifetime of charged particles in such a trap. The basic factor which determines the lifetime is the Coulomb scattering of the particles. This effect has been considered in detail by G. I. Budker [1]*. The calculation was carried out in the adiabatic approximation, i.e., it was assumed that an individual charged particle (which has not experienced collisions with other particles) remains in the trap for an arbitrary time because of conservation of the magnetic moment μ.

Since the magnetic moment of a charged particle in a magnetic field is only an approximate (adiabatic) invariant, it can change slowly. The theoretical estimates of this change [2] indicate only that as $\rho/R \to 0$, $\Delta\mu/\mu$ approaches zero faster than any power of ρ/R (ρ is the Larmor radius of the particle and R is the radius of curvature of the magnetic lines of force). The value of $\Delta\mu/\mu$ is undetermined for a finite value of ρ/R. In cases of practical interest (for example in the "ogra" system) the ratio R/ρ is between 1 and 10 and the number of reflection from the magnetic mirrors should be of the order of 10^5-10^6.

With this large number of reflections the accumulative effect of even the most insignificant changes in μ may lead to escape of the particle from the trap. In particular, any asimuthal inhomogeneity in the magnetic field may lead to escape [1]. Hence, an experimental study of the behavior of charged particles in adiabatic traps is of great interest.

In [3] and [4] there are reports of attempts to carry out such experiments; the basic feature of these experiments was the injection of particles into the trap. However, because of the uncertainties associated with the "extraction" of particles from the injector, the authors were not able to obtain definite results.

In order to overcome these difficulties, in the present work we have used β particles formed inside a trap which was filled with tritium. The density of charged particles was less than $10^4 cm^{-3}$ so that collective interactions could be neglected.

Experimental arrangement. The motion of β particles formed as a result of tritium decay inside the trap leads to ionization of the gas atoms. The ions and slow electrons can be collected by a weak electric field, which has no effect on the motion of the β particles (as is the case in an ionization chamber). The magnitude of the ionization current measured this way is proportional to the number of β particles produced per unit time (i.e., the tritium pressure) and the number of ion pairs formed by each β particle. In turn, the latter is proportional to the tritium pressure and the lifetime of the β particles in the trap.

If the escape of β particles is due to scattering on tritium atoms, the lifetime is inversely proportional to the pressure; hence the ionization current is directly proportional to the first power of the tritium pressure. However, if there is any other mechanism for the escape of β particles from the trap, when the pressure is reduced below some critical value, the lifetime of the β particles no longer depends on the tritium pressure and the ionization current depends on the square of the pressure. Thus the experiment consists of measuring the dependence of the ionization current on tritium pressure. From the value of the pressure at which there is a transition from a quadratic dependence to a linear dependence, it is then possible to determine that part of the lifetime of the β particle in the trap which is independent of the scattering on tritium atoms.

Description of the apparatus. The magnetic field of the trap is produced by means of an iron-clad electromagnet 9 and additional windings 11 (Fig. 1). The maximum field close to the pole pieces is H_{mir} = 5000oersteds and the field in the center of the chamber is H_0 = 600 oersteds. The ratio $H_{mir}/H_0 = \gamma$ can be varied over the limits 1-40.

Between the pole pieces of the magnet there is a glass chamber 1, on the inner surface of which are deposited aluminum electrodes 2-4. The chamber is heated under vacuum to a temperature of 400-450 °C for several days after which it is sealed off from the vacuum system. Then the chamber is joined to section 13, which contains a freshly prepared (with a small admixture of He^3) sample of uranium titride UT_3 with tritium activity of ~1 curie. This section also contains

*In this work only pair collisions were considered. At the present time the affect of collective interactions on particle escape from a trap has not been treated.

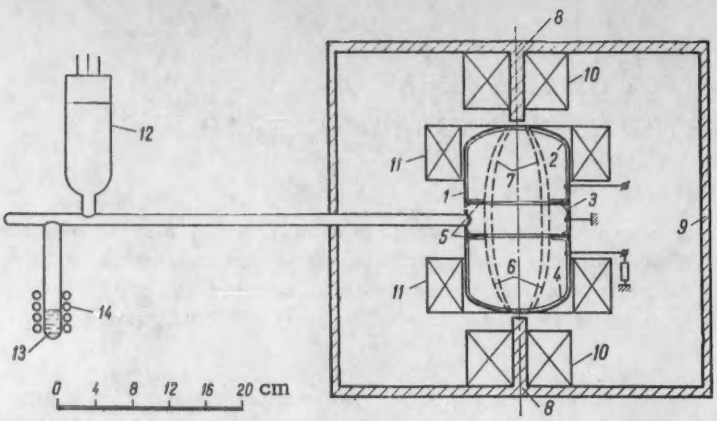

Fig. 1. Schematic diagram of the apparatus. 1) Glass chamber; 2) high-voltage electrode; 3) guard ring; 4) collector; 5) glass circular shoulders; 6) boundary of the operating volume for slow ions and electrons; 7) boundaries of the operating volume for fast β particles; 8) pole piece; 9) yoke; 10) and 11) coils; 12) ionization gauge; 13) UT_3; 14) UT_3 heater.

uranium powder which served as a getter for air, the residual pressure of which was $\sim 10^{-7}$ mm Hg. † When the UT_3 sample is heated the tritium pressure in the chamber increases (to approximately 10^{-3} mm Hg at approximately 100 °C); in cooling, the pressure falls (to $\lesssim 10^{-7}$ mm Hg at liquid nitrogen temperature).

The gas pressure in the chamber is measured by means of standard ionization gauges which are calibrated for tritium. The calibration is carried out by measuring the He^{3+} ion current formed as a consequence of β decay of tritium in the absence of the magnetic field (in the absence of trapping, the current bound with the ionization of gas at these pressures is too small to be measured). The ionization gauge also serves as a pump for removal of He^3.

The ionization current is measured by means of a standard electrometer amplifier with a threshold sensitivity of $5 \cdot 10^{-14}$ amp. Currents ranging from $5 \cdot 10^{-13}$ to $5 \cdot 10^{-9}$ amp are measured. The voltage source is a battery which is located in a shielded compartment. All the connections are made with shielded cable. The resistance of the glass between the collector and the surrounding electrode is approximately 10^{11} ohms and the input resistance of the amplifier is unshunted (10^8–10^{10} ohms).

Determination of the background currents. There are three basic sources of background current: He^{3+} ion current, secondary electron emission from the cathode due to β particles emitted from the walls of the chamber, and secondary emission due to β particles from the chamber volume itself, which strike the cathode.

When the magnetic field is on, the He^{3+} ion current is due exclusively to those ions which are formed within volume 6 (cf. Fig. 1), which is bounded by the lines of force tangent to the inner circular ribs of the chamber 5. This volume is computed from the known configuration of the magnetic field.

During the experiments it was noticed that a significant amount of tritium (approximately 10 millicuries) was deposited on the walls of the chamber. The time of deposition is several days so that in the individual experiments, which last several hours, the concentration of tritium on the walls can be assumed constant. The β particles produced from the decay of this tritium are not captured in the trap but strike the walls of the chamber after several revolutions, causing secondary electron emission. Because of the electrode shape which is used 2,4 (cf. Fig. 1), the background current is produced only by those secondary electrons which strike that part of the cathode contigous to the volume 6. This current is measured by freezing out the tritium ($p_T < 10^{-7}$ mm Hg).

The β particles formed in volume 6, which strike the cathode, also produce a secondary emission and background current proportional to the tritium pressure. In order to compute this component of a background current it is necessary to know the secondary emission factor; this quantity was measured separately and found to be equal to unity.

In all the subsequent measurements the background currents were substracted.

Control experiments. The dependence of ionization current on the collector voltage is measured (Fig. 2). The characteristic feature is reduction in current at higher voltages (> 750 v), at which point the electric field starts to have an effect on the motion of the β particles. The basic measurements are carried out at a collector voltage of approximately 200 v. The background currents

† The author wishes to express his gratitude to M. D. Senin and Yu. V. Gararinskii for preparation of the UT_3 sample and for preparing the chamber for the experiment.

remain constant at high collector voltages; this effect is evidence of the absence of discharges in the system.

In order to check whether or not the surface charges on the walls of the chamber have any effect on the results, measurements were carried out in which the polarity of the high voltage electrode was reversed. In all cases the current remained the same in absolute value.

Measurements were also made of the ionization current in a uniform magnetic field ($\gamma = 1$). Within the limits of experimental errors this current was found to be zero, indicating that the background currents were taken into account correctly.

Basic results. If another gas beside tritium is present in the trap, the ionization current to the collector 4 (cf. Fig. 1) depends on the partial pressures in the following manner:

$$I \sim \frac{p_T (p_T + \alpha p_f)}{p_T + p_0},$$

where p_T is the tritium pressure; p_f is the pressure of the foreign gas; p_0 is the tritium pressure at which escape of the β particles from the trap as a consequence of scattering on tritium atoms becomes comparable with escape for other reasons (including scattering on the foreign gas); $\alpha = \sigma_{if}/\sigma_{iT}$ (σ_i is the ionization cross section).

However, the current in the ionization gauge $I_M \sim (p_T + \alpha p_f)$ with the same value of α as in the expression for I because at electron energies above 200 v (anode potential of the ionization gauge), α is essentially independent of the electron energy.

Thus, the ratio of the ionization currents in the trap and the gauge is proportional to $p_T/(p_T + p_0)$. When $p_T = p_0$ this ratio is reduced by a factor of two as compared with the value for large p_T. An example of the determination of p_0 by the method described here is shown in Fig. 3.

The chief foreign gas in the present experiments is He^3. Almost all the tritium activity is contained in the UT_3 (no more than 10% of the tritium goes into the chamber). Hence, to a considerable degree, the He^3 which is formed sticks in the UT_3 crystal lattice and is removed therefrom by heating along with the tritium (in proportion to the amount of the latter). The coefficient of proportionality is determined in special experiments by freezing out the tritium. Knowing the He^3 pressure it is possible to find the pressure of the tritium from the reading of the ionization gauge.

We first consider the determination of the lifetime of the β particles in the trap which results from scattering on tritium atoms ($p_T \gg p_0$). To determine this quantity it is sufficient to know the energy loss of each β particle in the trap or the number of ion pairs formed by the β particles ‡; the latter is equal to the ratio of the ionization time to twice the He^{3+} ion current** from the volume bounded by the magnetic lines of force which start from the inner circular ribs of the chamber at a distance (cf. 7, Fig. 1) ($\overline{\rho^2}$ is the Larmor radius of the

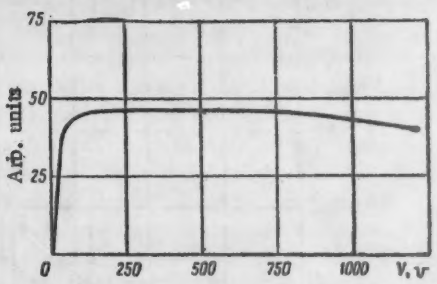

Fig. 2. Dependence of ionization current I on collector voltage V.

β-particles in the magnetic field H_0 averaged over the β-spectrum). The working volume is determined for each configuration of the magnetic field.

Knowing the energy loss of the β particles, using the conventional ionization loss formulas, we can compute the lifetime of the β particle in the trap by determining its path and the number of reflections from the magnetic mirrors. In order to determine the number of reflections a computation is made of the mean path of the β particle between reflections; depending on the configuration of the magnetic field this path varies between 15 and 20 cm. The relation between the energy loss of the β particles in the trap, ΔE, the number of reflections N, and the lifetime τ is shown in the table (mean initial energy of the β-particles of tritium is 6 kev.)

The dependence of the lifetime τ of the β particle in the trap [in units of the ionization stopping time $(2 \cdot 10^{-7})/p_T$ sec] on the various trap parameters is shown in Figs. 4-6 for the case $p_T \gg p_0$.

In Fig. 4 is shown the dependence of τ on the magnetic field H_0 for $\gamma = 5$. Each point represents the average of six measurements carried out at $p_T \sim 10^{-3}$ mm Hg. The indicated errors (as in the other figures) are statistical.

In Fig. 5 is shown the dependence of τ on H_0 for a given H_{mir}. A characteristic feature of this dependence is the maximum in τ, as predicted in [1]. The maximum is due to the fact that at small values of H_0 the escape of β particles across the magnetic field is intensified, while at large values of H_0 the escape of β particles through the mirrors is intensified (because of the reduction in γ). The location of the maximum corresponds to the theoretical estimates.

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‡It was assumed that an average of 60 ev is required for the formation of one ion pair.

**The He^{3+} ion current is doubled because of the fact that the fast β particles which are formed by it have an equal probability for striking the anode and the cathode and thus not producing a current in the measurement circuit.

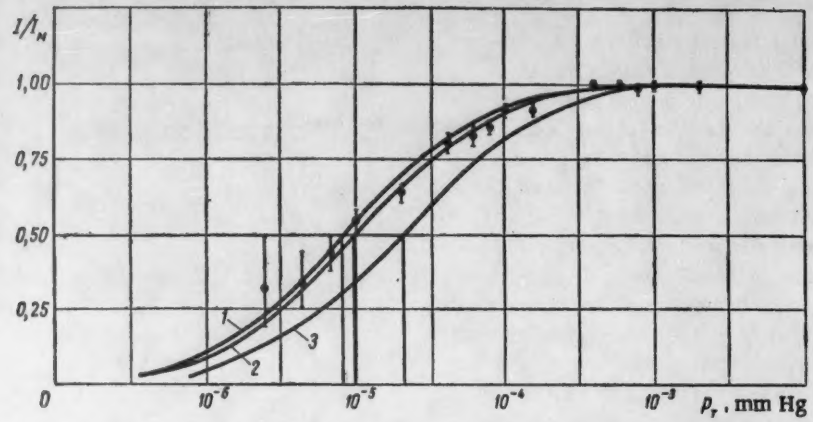

Fig. 3. Determination of p_0. The curves represent the function $p_T/(p_T + p_0)$; 1) $p_0 = 8 \cdot 10^{-6}$ mm Hg; 2) $p_0 = 10^{-5}$ mm Hg; 3) $p_0 = 2 \cdot 10^{-5}$ mm Hg.

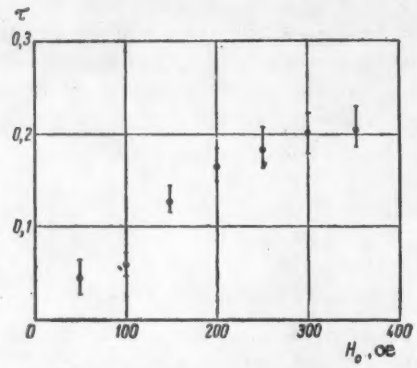

Fig. 4. The lifetime τ of β particles in the trap as a function of magnetic field at the center H_0 for $\gamma = 5$.

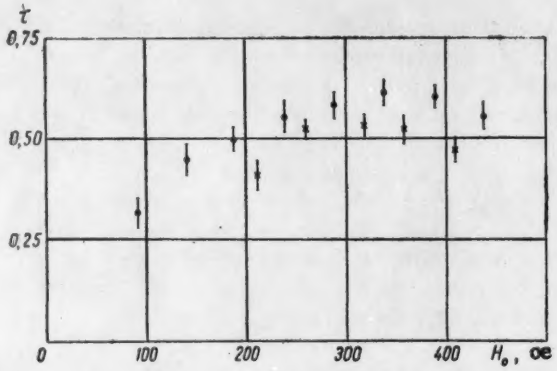

Fig. 5. The lifetime τ of β particles in the trap as a function of magnetic field at the center H_0.

In Fig. 6 is shown the dependence of τ on γ for $H_0 = 300$ oe. In accordance with [1] this dependence is proportional to the function

$$\psi(\gamma) = -\ln \operatorname{tg} \vartheta_0/2 - \cos \vartheta_0 \ (\sin^2 \vartheta_0 = 1/\gamma).$$

The quantity $\gamma = H_{mir}/H$ has different values for β particles formed in different regions of the chamber; in [1], however, for simplicity, it was presumed that this quantity is the same for all particles. Hence, an average was made of $\psi(\gamma)$, taking account of the fraction of β particles with different γ. The curve computed in this way was combined with the experimental points for large values of γ. The formal use of the results of [1] yields a combined calculated curve in which the mean value of the β particle energy is somewhat low (approximately 1.5 kev).

In order to find N and τ which correspond to the presence of other mechanisms for the escape of β particles from the trap (i.e., not connected with scattering on tritium atoms), one can use the data of the table, replacing p_T by p_0. As has already been noted, the chief mechanism is the scattering of β particles on He^3 atoms. It has been found from the experiments that the relation between p_0 and p_{He} can be expressed as follows:

$$p_0 = a p_{He} + b.$$

The residual value of p_0, equal to b, can be due both to the presence of traces of air in the trap as well as to possible changes in the magnetic moment of the individual β particles (without collisions).

For the magnetic field configurations which were used ($H_0 > 200$ oersted, $\gamma < 15$), b was not more than $2 \cdot 10^{-6}$ mm Hg. Assuming that there is no air in the trap it is possible to find the lower limit on the number of reflections from the magnetic mirrors associated with the change of μ for the individual β particle; in particular, assuming that $H_0 = 400$ oe, $H_{mir} = 4500$ oe, $N > 10^7$, and $\tau > 0.07$ sec (under these conditions the

Energy Loss, Number of Reflections, and Lifetime of β Particles in the Trap

ΔE, kev	$N \cdot p_T$, mm Hg	$\tau \cdot p_T \cdot 10^8$, sec · mm Hg
1	5,7	4
2	11,1	8,3
3	15,5	12
4	18,3	15
5	20,6	18,3
6	21,4	20,2

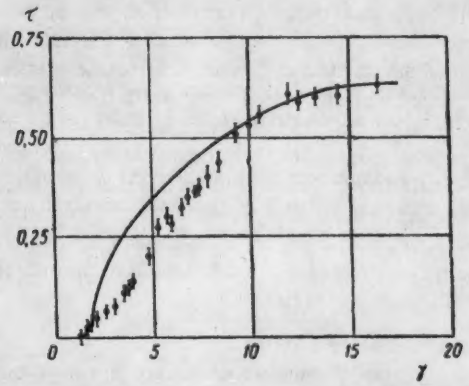

Fig. 6. The lifetime τ of the β particles in the trap as a function of γ (the solid curve is the theoretical curve).

H_0	H_{mir}	γ	ΔH/H, %	N
300	4000	13	0	$>6 \cdot 10^6$
			3	$>6 \cdot 10^6$
90	3600	40	0	$2 \cdot 10^5$
			9	$2 \cdot 10^4$
			15	$2 \cdot 10^4$
200	960	5	0	$>3 \cdot 10^6$
			4	$>3 \cdot 10^6$

β particle forms 65 ions pairs and loses approximately 4 kev before emerging from the trap).††

With certain magnetic field configurations the value of b is considerably greater than $2 \cdot 10^{-8}$ mm Hg; and this can be explained only by a change of μ for the individual β particle. For example, when H_0 is reduced to 90 oe and γ is increased to 40, the escape of β particles from the trap is found to be much greater ($N = 2 \cdot 10^5$).

The escape of β particles from the trap also increases if an azimuthal asymmetry is introduced. Under normal conditions the azimuthal asymmetry is less than 0.5 percent in the center of the trap and 4 percent at the poles. The artificial inhomogeneity is produced by means of coils located in the median plane of the magnetic field outside the chamber. In all cases, the introduction of an azimuthal asymmetry resulted in the reduction of the ionization current; apparently this effect is due to the change in the working volume of the trap. The results of the measurements obtained with the azimuthal asymmetry are given below (the magnitude of the additional azimuthal asymmetry ΔH/H):

Conclusions. The method which has been applied here makes it possible to obtain quantitative data concerning the behavior of charged particles in an adiabatic trap and is of interest for all traps in which magnetic mirrors are employed.

The lifetime of the β particles in the trap, associated with the Coulomb scattering on gas atoms, is found to be in satisfactory agreement with the theoretical predictions [1] to 10^7 reflections from the magnetic mirrors. The effects observed due to the introduction of azimuthal inhomogeneities in the magnetic field seem to be compatible with the results of a recent calculation [6].

We wish to take the opportunity to express our gratitude to G. I. Budker who took part in the present work and P. E. Spivak who was a great help in the initial stages of the experiment.

Note added in proof. We have recently become acquanted with similar experiments carried out by Gibson and Lauer (Bull. Amer. Phys. Soc. 3, 412, 1958). The details of this work became not been published.

LITERATURE CITED

1. G. I. Budker, Coll.:Plasma Physics and the Problem of a Controlled Thermonuclear Reaction 3 [in Russian] (Izd. AN SSSR, 1958) p. 3.
2. R. Kulsrud, Phys. Rev. 106, 205 (1957).
3. A. Bishop, Project Sherwood. USA (Mass., Addison-Wesley Publishing Company, Inc. 1958).
4. G. M. Antropov, V. A. Belyaev, and M. K. Romanovskii, Coll.: Plasma Physics and the Problem of a Controlled Thermonuclear Reaction. 3 [in Russian] (Izd. AN SSSR, 1958) p. 250.
5. Mott and Massey, Theory of Atomic Collisions [Russian translation] (IL, 1951).
6. B. V. Chirikov, Atomnaya Énergiya 6, 630 (1959). ‡‡

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††Since the cross section for scattering of β particles by air atoms is $Z(Z+1)/2$ times greater than for tritium atoms the residual pressure of air required to explain the observed value of b amounts to $\sim 7 \cdot 10^{-8}$ mm Hg. The partial pressure of the air was not measured directly in the present experiments.

‡‡Original Russian pagination. See C. B. translation.

RESONANCE PROCESSES IN MAGNETIC TRAPS

B. V. Chirikov

An analysis is made of resonances between the Larmor rotation of charged particles in a magnetic field and the slow oscillations along the field lines. It is shown that under certain conditions these resonances can lead to the complete exchange of energy between the degrees of freedom of a particle and can cause its escape from the trap. Consideration is also given to the effect of resonances on adiabatic processes associated with a variation of the magnetic field as a function of time.

One of the methods of thermally isolating a plasma in order to realize a controlled thermonuclear reaction is the application of so-called adiabatic traps (traps with magnetic mirrors) proposed by G. I. Budker [1]. Similar systems have been proposed by York [2] and have been considered in [3]. In recent years this approach has received a good deal of attention [4, 5]; for this reason further investigations of systems of this kind are of great interest.

The action of an adiabatic trap is based [1] on the conservation of orbital magnetic momentum of a charged particle in a magnetic field [$\mu = (Mv_\perp^2/2H)$; $v_\perp$ is the component of the particle velocity in the direction perpendicular to the magnetic field H]. Obviously, a necessary but not sufficient condition for the realization of a trap is the possibility of containment of an individual charged particle. The lifetime of such a particle in a trap, is not infinite since the magnetic moment is only an adiabatic invariant, i.e., it can change slowly and this change leads to a redistribution of energy between the longitudinal and tranverse degrees of freedom of the particle, and ultimately to its escape from the trap.

The change of an adibatic invariant has been considered by a number of authors (cf., for example, [6–8]); however, it is only in [7] that calculations have been applied to the concrete result of a harmonic oscillator, in particular :

$$\frac{\Delta I}{I} = \frac{2\Delta^{(q)}}{(2\omega_0)^{q+1}} \cdot \cos\left(2\theta_0 - \frac{\pi q}{2}\right), \qquad (1)$$

Where I is the adiabatic invariant; $\Delta^{(q)}$ is the discontinuity of the qth derivative of $\omega(t)$; θ_0 , ω_0 are the phase and frequency of the oscillator at the discontinuity in the derivative. The chief shortcoming of the expression given above is its asymptotic character. This means that is valid only for $1/\omega T \to 0$ (T is the characteristic time for a change in $\omega(t)$). For finite values of the adiabaticity parameter $1/\omega T$,(1) is not always valid (the conditions for validity are given in the Appendix). In the particular case in which $\omega(t)$ is an analytic function,(1) gives $\Delta I/I = 0$. This means that when $1/\omega T \to 0$, the quantity $\Delta I/I$ approaches zero faster than any power of the parameter $1/\omega T$ (for example as $e^{-\omega T}$), but remains unknown . Thus, the usual asymptotic expansion in powers of a small parameter of the type $1/\omega T$ is not feasible in the present case.

In the present paper we consider another approach to the problem. This approach is based on a simple physical model of the resonances between the Larmor rotation of the charged particle and the slow oscillations of the particle along the magnetic field lines.* Such resonances are possible in spite of the difference in frequencies if the slow oscillations of the particle are anharmonic (i.e., contain higher harmics of the fundamental frequency). In particular, the effect of such resonances leads to a change in the magnetic moment of the individual particle (without collisions).

1. BASIC EQUATIONS

In the present paper we do not attempt to obtain calculation formulas; main attention is concentrated on the physical processes which take place in the motion of a charged particle in a magnetic trap. For this reason we shall limit ourselves to an analysis of the simple Hamiltonian used in [6] (M = 1):

$$\mathcal{H} = \frac{p_x^2 + p_y^2 + \omega^2(x)\, y^2}{2}; \quad p_x = \dot{x}; \quad p_y = \dot{y} \qquad (1.1)$$

Here x and y are the coordinates along the lines of force and perpendicular to the lines of force, respectively; ω is the Larmor frequency.

The equations of motion are

$$\ddot{y} = -\omega^2 y; \quad \ddot{x} = -\omega \frac{d\omega}{dx} y^2. \qquad (1.2)$$

Since the oscillations along the x axis are slow ($\Omega \ll \omega$), the solution for y is of the form

$$y = \rho \cos\theta; \quad \theta = \int \omega\, dt + \varphi, \qquad (1.3)$$

(ρ is the Larmor radius of the particle) and

$$\ddot{x} = -\omega \frac{d\omega}{dx} \frac{\rho^2}{2}(1 + \cos 2\theta).$$

Since ($\omega\rho^2/2$) = I , where I is related to the magnetic movement by the relation $I = c\mu/e$, we have

$$\ddot{x} + I \frac{d\omega}{dx} = -I \frac{d\omega}{dx} \cos 2\theta. \qquad (1.4)$$

* The role of resonances in change of an adiabatic invariant has been considered in [9].

Thus, the motion along the x axis is oscillatory with a potential energy $I\omega(x) = \mu \overline{H}(x)$; on this oscillatory motion is superimposed a fast periodic perturbation characterized by frequency 2ω. Usually this perturbation is neglected because $\omega \gg \Omega$; however, if the oscillations along the x axis contain high harmonics of the fundamental frequency it is possible to have a resonance between the fast periodic perturbation $I(d\omega/dx)\cos 2\theta$ and one of these harmonics

The effect being described here can be approached from another point of view. We consider the equation $\ddot{y} + \omega^2(t)\, y = 0$, in which the dependence of ω on time is related to the oscillations along the x axis. The period for a change of the function $\omega(t)$ is much larger than $1/\omega$; but if $\omega(t)$ contains high frequencies, up to ω, one of these can cause a parametric resonance.

Since the total energy of the particle $\mathcal{H}$ is conserved, both resonances being considered lead to a redistribution of the energy of the particle between the various degrees of freedom.

In order to investigate these resonances we make use of a method described in [10]. First we introduce the Hamiltonian $\mathcal{H}_y$, which describes the motion along the y axis:

$$\mathcal{H}_y = \frac{p_y^2 + \omega^2(t)\, y^2}{2}. \tag{1.5}$$

Then $\frac{d}{dt}\mathcal{H}_y = \frac{\partial}{\partial t}\mathcal{H}_y = \omega\dot{\omega}y^2$. The change in the adiabatic invariant $I = \mathcal{H}_y/\omega$ is given by

$$\frac{dI}{dt} = \dot{\mathcal{H}}_y/\omega - \mathcal{H}_y\dot{\omega}/\omega^2 = \dot{\omega}\,(y^2 - \overline{y^2}), \tag{1.6}$$

where the bars denote averages over phase which changes with frequency ω. Regarding ω as a parameter, we obtain the frequency correction $\dot{\varphi}$ (1.3) [10]:

$$\dot{\varphi} = -\frac{\omega\dot{\omega}}{\dot{y}}\left[\omega y^2\left(\frac{\partial y}{\partial I}\right)_{\omega,\,\theta} + \left(\frac{\partial y}{\partial \omega}\right)_{I,\,\theta}\right] = -\frac{\dot{\omega}}{2\omega}\sin 2\theta. \tag{1.7}$$

We also introduce the Hamiltonian $\mathcal{H}_x$ which describes the motion along the x axis (1.4):

$$\mathcal{H}_x = \frac{p_x^2}{2} + I\omega\,(1 + \cos 2\theta). \tag{1.8}$$

Taking

$$x = x(I, \vartheta);\quad \vartheta = \int \Omega(I)\, dt + \psi \tag{1.9}$$

and noting that the quantity $W_x = p_x^2/2 + I\omega$, is equal to the total Hamiltonian $\mathcal{H}$, which is conserved, we have

$$\dot{W}_x = \frac{\partial W_x}{\partial t} + [W_x, \mathcal{H}_x] = \dot{I}\omega - \dot{x}\frac{d\omega}{dx} I\cos 2\theta = 0,$$

where [,] denotes Poisson brackets. Whence

$$\dot{I} = I\frac{\dot{\omega}}{\omega}\cos 2\theta, \tag{1.10}$$

which coincides with (1.6). As for (1.7) we obtain for $\dot{\psi}$ (1.9) of [10]:

$$\dot{\psi} = \frac{\Omega}{\dot{x}}\left(\frac{\partial x}{\partial I}\right)_\theta \dot{I} = I\left(\frac{\partial x}{\partial I}\right)_\theta \frac{\Omega}{\omega}\frac{d\omega}{dx}\cos 2\theta. \tag{1.11}$$

We may note that (1.7), (1.10), and (1.11) are exact for the Hamiltonian which has been used (1.1).

2. FIRST-ORDER RESONANCES

We now integrate (1.10), expanding the right side in a Fourier series. The function 2θ describes the frequency-modulated oscillation:

$$\dot{\theta} = \omega + \dot{\varphi} = \bar{\omega} + \dot{\varphi} + \sum_n \omega_n \cos 2n\vartheta,$$
$$\theta = \varphi + \bar{\omega}t + \sum_n \frac{\omega_n}{2n\Omega}\sin 2n\vartheta. \tag{2.1}$$

The bars here and below denote averages over phase which change with frequency Ω. Making some simple transformations we find

$$\cos 2\theta = \frac{1}{2}\sum_n (F_{1n} \pm F_{2n})\cos 2(\bar{\omega}t + \varphi \pm n\vartheta), \tag{2.2}$$

where the summation is taken over both signs (both signs change simultaneously). The expansion of $\omega(t)$ has only cosine symmetry with respect to the turning point ($\dot{x}=0$); the factor of 2 in (2.1) is due to the symmetry of $\omega(x)$ with respect to the median plane of the magnetic field. The Fourier coefficients F_{1n} and F_{2n} are determined by the relations

$$\left.\begin{aligned}\cos\left(\sum_n \frac{\omega_n}{n\Omega}\sin 2n\vartheta\right) &= \sum_n F_{1n}\cos 2n\vartheta,\\ \sin\left(\sum_n \frac{\omega_n}{n\Omega}\sin 2n\vartheta\right) &= \sum_n F_{2n}\sin 2n\vartheta.\end{aligned}\right\} \tag{2.3}$$

Suppose now that

$$\frac{\dot{\omega}}{\omega} = \sum_m \Omega_{1m}\sin 2m\vartheta. \tag{2.4}$$

Multiplying (2.2) and (2.4) we obtain the equation

$$\frac{dI}{dt} = I\sum_{\bar{\omega}\approx l\Omega} P_l\cos\psi_l. \tag{2.5}$$

The condition $\bar{\omega} \approx l\Omega$ shows that in all the summations it is necessary to keep only one term, the frequency of change of which is close to zero. This is the resonance term, which gives the largest contribution to the change in I.

$$\psi_l = 2(\bar{\omega}t + \varphi_1 - l\vartheta);\quad \varphi_1 = \varphi - \pi/4,$$
$$4P_l = -\sum_{m-n=l}\Omega_{1m}(F_{1n} + F_{2n}) + \tag{2.6}$$
$$+\sum_{n-m=l}\Omega_{1m}(F_{1n} - F_{2n}) -$$
$$-\sum_{m+n=l}\Omega_{1m}(F_{1n} - F_{2n}). \tag{2.7}$$

Equation (2.5) must be supplemented by the equation for $\dot{\psi}_l$ (1.7); (1.11) :

$$\dot{\psi}_l = 2\left(\bar{\omega} - l\Omega - \frac{\dot{\omega}}{2\omega}\sin 2\vartheta - I\frac{\partial x}{\partial I}\frac{\Omega}{\omega}\frac{d\omega}{dx}\cos 2\vartheta\right).$$

Assuming that

$$2I\frac{\partial x}{\partial I}\frac{d\omega}{dx}\frac{\Omega}{\omega} = \sum_m \Omega_{2m}\cos 2m\vartheta, \qquad (2.8)$$

we have

$$\frac{d\psi_l}{dt} = 2(\bar{\omega} - l\Omega) - \sum_{\bar{\omega}\approx p\Omega} Q_p \sin\psi_p, \qquad (2.9)$$

where Q_p is determined by the expression

$$-4Q_p = \sum_{m-n=p}(F_{1n}+F_{2n})(\Omega_{2m}+\Omega_{1m}) + \sum_{n-m=p}(F_{1n}-F_{2n})(\Omega_{2m}-\Omega_{1m}) + \sum_{m+n=p}(F_{1n}-F_{2n})(\Omega_{2m}+\Omega_{1m}). \qquad (2.10)$$

3. HIGHER- ORDER RESONANCES

Equations (2.5) and (2.9), which will be investigated below, are approximate, not only because the nonresonance terms have been omitted (the latter leads only to a small variation in I) but because they do not take account of all the resonances. In the derivation of (2.5) and (2.9) we have proceeded from (2.1) and (2.2), assuming that φ and ψ are constant; actually they contain small periodic components, as is seen from (1.7) and (1.11). As can be shown, this leads to the appearance of additional resonances which are determined by the condition $k\bar{\omega} = l\Omega$ ($k \geq 2$). (The coefficient k will be called the order of the resonance.) There are also other effects which lead to higher-order resonances. An exact calculation of these effects has not been carried out. However, analysis of particular cases shows that the higher-order resonances are described by equations which are similar to (2.5) and (2.9) with the substitutions $\bar{\omega} \to k\bar{\omega}$; $P_l \to P^{(k)}_l \simeq P_l\alpha_k$ and $Q_l \to Q^{(k)}_l \simeq Q_l\alpha_k$, where α_k is assumed to be equal to the largest of the quantities $(\rho/R)^{2(k-1)}$ or $(Q_l/\Omega)^{k-1}$ (R is the radius of curvature of the magnetic lines of force). In the first case (ρ/R) both integral and half integral values of k are possible. In the second case, (Q_l/Ω) can only be integral. It is apparent that the rule which has been formulated applies only for rough estimates and that the question requires further study.

4. STATIONARY CASE

By stationary here we mean the absence of any explicit dependence of ω in (1.1) on time ($\partial\omega/\partial t = 0$) in contrast to the nonstationary state, in which $\omega = \omega(x, t)$.† The stationary case corresponds to a magnetic field which is axially symmetric and constant in time. The nonstationarity is produced as a consequence of azimuthal inhomogenities‡ (because of particle drift) as well as an explicit dependence of magnetic field on time.

It is well known (cf. for example [11]) that in the case being considered here (2.5) and (2.9) define a series of instability regions for $\bar{\omega} = l\Omega$; the widths of these regions are given by $\Delta_p(\bar{\omega} - l\Omega) \sim Q_l$. As will be shown below, there is no need to investigate these regions in detail; it is important to note only that they do not overlap i.e., the width of these regions Q_l is smaller than the distance between them 2Ω. This result follows directly from an estimate for Q_l (I.2)**: $Q/\Omega \lesssim \sqrt{\Omega/\bar{\omega}} \ll 1$.

The higher-order resonances have no effect on the inequality given above since the total width of the resonances is approximately $\sum_k kQ^{(k)}_l \sim Q_l\sum_k k\alpha_k \sim Q_l$, ($\alpha_k \ll 1$) (cf. Section 3.).

But in this case the instability regions in general do not play important roles because of the nonlinearity of the oscillations; more precisely, because of the dependence of the frequencies $\bar{\omega}$ and Ω on I. Even for particles which come close to the intability regions, I never varies monotonically, but executes oscillations about the resonance value [10]. By analogy with the oscillations of charged particles in accelerators we will call these oscillations phase oscillations. They can be investigated by means of an equation which is obtained by eliminating $\dot{I}$ in (2.5) and (2.9) :

$$\frac{d^2\psi_l}{dt^2} = 2\frac{\partial}{\partial t}(\bar{\omega} - l\Omega) + 2IP_l\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\cos\psi_l. \qquad (4.1)$$

Here and below we neglect the term with Q_l as is justified under the conditions $Q_l^2 \ll \left|IP_l\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right|$ [10], which are always satisfied. The amplitude of the change of frequency of the phase oscillations is

$$\Delta_{ph}(\bar{\omega} - l\Omega) \simeq 2\sqrt{\left|IP_l\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right|}, \qquad (4.2)$$

and the frequency of the phase oscillations is

$$\Omega^2_{ph} \simeq \left|2IP_l\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right|. \qquad (4.3)$$

The case in which the amplitude (4.2) becomes comparable with or greater than the distance between the resonances 2Ω requires special analysis (cf. Section 6).

5. NONSTATIONARY CASE (RAPID PASSAGE THROUGH RESONANCE)

If the frequencies $\bar{\omega}$ and Ω depend on the time explicitly and the difference $\bar{\omega} - l\Omega$ changes, there is a

† The dependence of $\omega(t)$ encountered above is not explicit (in terms of x).

‡ Strictly speaking the Hamiltonian in (1.1) applies in an axially symmetric field. However, if the magnetic field does not change very much in the drift of particles in a time of approximately $1/\Omega$, the form of (1.1) can be maintained by introducing an explicit dependence for ω on t.

** (I.1)–(I.3) refer to equations in the Appendix.

passage through the resonances and a change in I occurs. First we consider the case of rapid passage; we neglect the rate of change of the frequencies $\bar{\omega}$ and Ω because of the change in I as compared with the rate of change of these quantities due to the explicit dependence on time :

$$A=\left|\frac{IP_l\,\frac{\partial}{\partial I}(\bar{\omega}-l\Omega)}{\frac{\partial}{\partial t}(\bar{\omega}-l\Omega)}\right|\ll 1.$$

In this case (2.5) and (2.9) are integrated directly and in the first approximation (in $\Delta I/I$) :

$$\Delta I=\sqrt{\pi}I\sum_{\bar{\omega}\approx l\Omega}\frac{P_l\cos(\psi_{0l}+\pi/4)}{\sqrt{\left|\frac{\partial}{\partial t}(\bar{\omega}-l\Omega)\right|}}.$$

Here ψ_{0l} is the value of the phase ψ_l at resonance ($\dot{\psi}_l = 0$). For a random (phase distribution ψ_{0l} for different passages through resonance $\overline{\Delta I}=0$, and

$$\overline{(\Delta I)^2}=\frac{\pi}{2}I^2\sum_l\frac{P_l^2}{\left|\frac{\partial}{\partial t}(\bar{\omega}-l\Omega)\right|}, \qquad (5.3)$$

where the summation extends over all the resonances indicated and the bar denotes averages over the phase ψ_{0l}. In the next approximation

$$\overline{\Delta I}=\frac{1}{2}\frac{\partial}{\partial I}\overline{(\Delta I)^2}+$$
$$+\frac{\pi}{4}\sum_l\frac{IP_l}{\left|\frac{\partial}{\partial t}(\bar{\omega}-l\Omega)\right|}\left[Q_l-\frac{\partial}{\partial I}(P_lI)\right]. \qquad (5.4)$$

The first moment (5.4) characterizes the systematic change of I while the second (5.3) denotes the "scatter" in I. A knowledge of both moments is sufficient for setting up a Fokker-Planck equation; the solution of this equation can be used to find the flux of particles on the forbidden cone [1]. However, as is apparent from the expressions for the moments, this equation is extremely complicated. For this reason we consider a simpler method of estimating the variation in I.

It follows from (5.4) that $\overline{\Delta I}/I\sim\overline{(\Delta I)^2}/I^2$. If $\overline{\Delta I}/I\ll 1$, the effect of the first moment can be completely neglected $\{[\overline{(\Delta I)^2}/I^2]^{\frac{1}{2}}\gg\overline{\Delta I}/I\}$; if $\overline{\Delta I}\gtrsim I$, the effects due to both moments are of the same order of magnitude. Hence, in making an estimate it is sufficient to study the variation of $\overline{(\Delta I)^2}$ alone. The condition for escape of particles from the trap will then have the form $\overline{(\Delta I)^2}\simeq(I_0-I_c)^2$, where I_0 is the initial value of I and I_c is the value at the surface of the forbidden cone.

In unit time $\frac{k}{\Omega}\left|\frac{\partial}{\partial t}(\bar{\omega}-l\Omega)\right|$ resonances occur so that taking account of (5.3) we have

$$\frac{d}{dt}\overline{(\Delta I)^2}=\frac{\pi}{2}\frac{kI^2(P^{(k)})^2}{\Omega}. \qquad (5.5)$$

This ordinary differential equation can be solved easily by numerial or approximation methods. It is obvious that in order for (5.5) to apply, the variation of I in passage through one resonance must be small compared with I.

The index k in (5.5) denotes the order of the resonances which are traversed and is determined by the range of variation $\bar{\omega}-l\Omega$ because of the explicit dependence on time :

$$k=\Omega/\Delta_t(\bar{\omega}-l\Omega). \qquad (5.6)$$

In particular, if there is an azimuthal inhomogeneity in the magnetic field, we can estimate k from the formula $k\approx(\Omega/\bar{\omega})/(\Delta H/H)$, which is obtained from $\Delta_t(\bar{\omega}-l\Omega)/\bar{\omega}\simeq\Delta H/H$.††

As an example we carry out a comparison of the obtained estimates with the exact asymptotic formula (1) [7]. From (I.3) for P and (5.5) we find $\Delta I/I\simeq$ $\simeq\frac{\Delta^{(q)}\sqrt{l\Omega}}{\sqrt{\pi}(2\omega)^{q+1}}$ or, in a time $\Delta t=\pi/2\Omega$ corresponding to a monotonic change of $\omega(t)$ in one direction, as assumed in [7] : $(\Delta I/I)_1\simeq\frac{\Delta^{(q)}}{\sqrt{2}(2\omega)^{q+1}}$, which agrees with (1) in order of magnitude.

6. CRITERION FOR STOCHASTIC PROCESS

Equations (5.3)–(5.5) are based on the assumption that the process is stochastic, i.e. that the phases ψ_{0l} are random. We now investigate the conditions for which this assumption is justified.

For simplicity we consider periodic passage through a single resonance (first order) after an equal time interval $T/2$. In accordance with (5.2) $\Delta I\sim\sum_n\cos\psi_n$, where ψ_n is the phase at resonance. If the frequencies $\bar{\omega}$ and Ω are independent of I, $\psi_{n+1}-\psi_n=\dot{\psi}_0=$ $=2\int_{t_n}^{t_n+T/2}(\bar{\omega}-l\Omega)\,dt=\text{const}$ and, as a result,

$$\Delta I\sim\sum_n\cos n\psi_0\leqslant 1/\sin\psi_0/2. \qquad (6.1)$$

In this case ΔI is limited and the process is not stochastic. Now we introduce the nonlinearity of the oscillations. After each passage through resonance the frequency $\bar{\omega}-l\Omega$ will changed by an amount $(\Delta\omega)_n=(\Delta\Omega)_n\times$ $\times\frac{\partial}{\partial I}(\bar{\omega}-l\Omega)$ which, in the next passage, leads to an additional change of phase $\psi_{1n}=T(\Delta\omega)_n$. When $\psi\ll 1$, we arrive at the preceding case. However, if $\psi_1\gg 1$, then it is precisely ψ_1 which determines the change of phase ψ_n. In contrast with (6.1) this change is not uniform but depends on the preceding phase

†† It can be shown that an azimuthal inhomogeneity does not lead to a change in the frequencies $\bar{\omega}$ and Ω because the particle drift is perpendicular to ∇H. However, if we take account of the motion of the particles along the lines of force, it is easy to show that H in the orbit of the particle will be changed and, moreover, that as $\Delta H/H$ it is necessary to take the maximum value of the inhomogeneity along the lines of force.

$[\psi_{1n} \sim (\Delta\omega)_n \sim (\Delta I_n) \sim \cos\psi_n]$; moreover, an insignificant change in the preceding phase can cause a change of the subsequent phase by 2π. It will be apparent that in this case the succession of phases ψ_n will be essentially random. However there is no rigorous proof of this statement; we will adopt it as a provisional working hypothesis. Then the criterion that the process be stochastic becomes

$$\nu_1 = \frac{2}{\sqrt{\pi}} \left| \frac{IP_l T \frac{\partial}{\partial I}(\bar{\omega} - l\Omega)}{\sqrt{\left|\frac{\partial}{\partial t}(\bar{\omega} - l\Omega)\right|}} \right| \gg 1. \qquad (6.2)$$

Similar criteria have been obtained in [12] and [13] by means of numerical calculations of the motion of a nonlinear oscillator under the influence of short periodic pulses. The authors introduce a quantity ν_1 as a criterion for instability; the relation between this criterion and the stochastic process is not considered. According to the data of this work an instability starts when $\nu_1 = \pi$.

We can now give the criterion which has been obtained a somewhat different physical meaning. If $\omega(x, t)$ is periodic in t, each harmonic of the expressions in (2.5) and (2.9) are found to be modulated at some frequency $\Omega_d = 2\pi/T$ and can be expanded in new harmonic components with frequencies $2(\bar{\bar{\omega}} - l\bar{\Omega}) \pm p\Omega_d$ ($\bar{\bar{\omega}}$ denotes averages over phases which change at the frequencies Ω, and Ω_d, while $\bar{\Omega}$ denotes averages over phases which vary with frequency Ω_d and with coefficients $P_{lp} \simeq P_l \sqrt{\frac{\Omega_d}{2\Delta_l(\bar{\omega} - l\Omega)}}$ (cf. Appendix, Section 1).

Substituting the last expression in (6.2) and taking $\left|\frac{\partial}{\partial t}(\bar{\omega} - l\Omega)\right| \simeq \frac{\Delta_l(\bar{\omega} - l\Omega)}{2}\Omega_d$, we obtain

$$\nu_2 = 4\sqrt{\pi}\frac{\Omega_{ph}^2}{\Omega_d^2} \gg 1, \qquad (6.3)$$

where $\Omega_{ph}^2 = \left|2IP_{lp}\frac{\partial}{\partial I}\left(\bar{\bar{\omega}} - l\bar{\Omega} \pm \frac{p\Omega_d}{2}\right)\right|$ is the square of the frequency of the phase oscillations for the new system of resonances (4.3) and Ω_d is the spacing between them.

We now apply the criterion (6.3) to the stationary case (cf. Section 4). Using (4.3) and taking account of the fact that the spacing between the resonances is 2Ω, we have

$$\varkappa = \frac{\left|2\sqrt{\pi}IP_l\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right|}{\Omega^2} \gg 1. \qquad (6.4)$$

If the condition in (6.4) is satisfied we have a stochastic change in I.

Apparently this effect has been found in [14]; using numerical methods the authors of this paper have studied the motion of a charged particle in an adiabatic trap. They found that close to the forbidden cone there is a region of "unstable" orbits which lead out of the trap stochastically. We apply the criterion (6.4) to the present work [14]. We determine P_l from (2.5) in the same way as was done in the example in Section 5:

$$(\Delta I/I)_{1/2} \simeq \pi P_l/\Omega,$$

where $(\Delta I/I)_{1/2}$ is the relative change in I per half period of the slow oscillation (π/Ω). This quantity has also been computed in [14]. Assuming that $\left|\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right| \simeq \bar{\omega}/I$, from (6.4), we find that the instability starts for $(\Delta I/I)_{1/2} \gtrsim 0.1$, whereas from the work cited [14] it follows that $(\Delta I/I)_{1/2} \gtrsim 0.02$. The discrepancy is not necessarily important if one remembers that the estimates which have been used are very crude.

7. NONSTATIONARY CASE (SLOW PASSAGE THROUGH RESONANCE)

The condition for slow passage through resonance is obviously $A \gg 1$ (5.1). As has been shown in [10], there are two basic modes for slow passage: capture and single passage. An important feature of the second mode is the independence of ΔI on the phase of the oscillations and the reversibility of the process associated with this even if the stochastic conditions in (6.2) are satisfied. Hence, for periodic slow passage through the same resonance in both directions, I will experience only small oscillations.

The capture mode means that in a change of the frequencies $\bar{\omega}$ and Ω, because of the explicit dependence on time, I automatically changes in such a way that the resonance condition $\bar{\omega} \approx l\Omega$ is satisfied for the entire time. It is apparent that for a periodic change in the frequencies $\bar{\omega}$ and Ω the process will be completely reversible.

However, capture can have an important effect on adiabatic processes connected with the considerable change in the magnetic field in time since in this case the additional condition $\bar{\omega}/\Omega = \text{const}$ must be satisfied. A basic difficulty is the fact that the capture region is small. The width of this region around each resonance is approximately, [10], $2\Delta_{ph}(\bar{\omega} - l\Omega) \sim \Omega_{ph}$ (4.2). For a uniform distribution of particles over I (consequently over frequency), the fraction of captured particles is approximately Ω_{ph}/Ω. However, it is precisely this ratio which must be small according to the stochastic criterion in (6.4).

8. COMPARISON WITH EXPERIMENT

To the best of our knowledge the single work in which quantitative data had been obtained concerning the change of an adiabatic invariant is the experimental work carried out by S. N. Rodionov [15]. A comparison of his experimental data with the theoretical results obtained above has been carried out for three magnetic field configurations (cf. Table). In order to find the Fourier coefficient Ω_{1m} the magnetic field at the of the system $[H(x) \sim \omega(x)]$ was approximated by a function of the form $1/(x + b)^2$, where x is the distance to the turning point ($\dot{x} = 0$); b was chosen to obtain the

Comparison of Theoretical and Experimental Data

№	γ	ρ/R	$\frac{\Delta H}{H}$,%	h	A	ν	κ	N (calculated)	N (experimental)
1	13	$6\cdot10^{-3}$	<4	2,5	—	$<2\cdot10^{-6}$	$2\cdot10^{-8}$	∞	$>6\cdot10^{6}$
			3	3,5	—	$<2\cdot10^{-6}$	$2\cdot10^{-8}$	∞	$>6\cdot10^{6}$
2	40	$5\cdot10^{-2}$	<4	4	—	$3\cdot10^{-3}$	0,4	∞	$\cdot10^{5}$
			9	2	10^{-2}	2	0,4	$8\cdot10^{3}$	$2\cdot10^{4}$
			15	1,5	$2\cdot10^{-2}$	2	0,4	$6\cdot10^{3}$	$2\cdot10^{4}$
3	5	$3\cdot10^{-3}$	<0,5	13,5	—	$<8\cdot10^{-6}$	$4\cdot10^{-7}$	∞	$>3\cdot10^{6}$
			4	2	—	$<8\cdot10^{-6}$	$4\cdot10^{-7}$	∞	$>3\cdot10^{6}$

best agreement. The accuracy of the approximation was 20—50 %. The following provisional values were assumed: the mean distance from the particle to the axis of the system in the median plane of the magnetic field $r_1 = 2$ cm; the radius of curvature of the magnetic lines of force $R = 2/n$ cm, the magnetic field decay index $n = (\gamma - 1)/640$; $\gamma = H_{mir}/H_0$, where H_{mir} is the maximum field at the axis of the system (magnetic mirror) and H_0 is the minimum field at the axis of the system.‡‡

The change in I was found from (5.5). I_0 was chosen in order to make $v_\perp \sim v_\parallel$. At the outset (for $I \sim I_0$), I was changed most slowly both because of the higher order of the traversed resonances [higher Ω, cf. (5.6)] and because of the smallness of P_l (the smoother function $\dot{\omega}/\omega$, and the smaller Ω_{1m}). It was assumed that it was sufficient to determine the number of reflections from the magnetic mirrors N leading to that change in I ($\Delta I_{\frac{1}{2}}$) in order that the order of the traversed resonances be reduced by $\frac{1}{2}$ *** since, after this, the rate of change of I increases. It was assumed that $\Delta I_{1/2}/I \simeq {}^1/_2 k \ll 1$ (5.6). Taking account of the relation $dt = dN(\pi/\Omega)$, from (5.5) we have

$$N \approx \frac{\Omega^2}{2\pi^2 k^3 (P^{(k)})^2}. \qquad (8.1)$$

The coefficient P was estimated from Eq. (I.1) and the criteria A, ν, and κ were estimated from (5.1), (6.2), and (6.4) It was assumed that

$$\left|\frac{\partial}{\partial I}(\bar{\omega} - l\Omega)\right| \simeq \bar{\omega}/I; \quad \left|\frac{\partial}{\partial t}(\bar{\omega} - l\Omega)\right| \simeq$$
$$\simeq \frac{\Delta_t(\bar{\omega} - l\Omega)}{2}\Omega_d \simeq \frac{1}{2}\left(\frac{\Delta H}{H}\right)\Omega_d\bar{\omega}.$$

The frequency of particle drift $\Omega_d = v_d/r$ was estimated from the formula [11]:

$$\frac{\Omega_d}{\Omega} \simeq \frac{n}{2}(\rho_1/r_1)^2 \frac{\omega_1}{\Omega}\frac{v^2}{v_\perp^2}\left(1 + \frac{\overline{v_\parallel^2}}{v^2}\right). \qquad (8.2)$$

The results of the calculations are shown in the Table. The data in the last column are taken from [15]. An actual comparison can be carried out only for the field configuration No. 2.††† With ΔH/H equal to 9 and 15% there is satisfactory agreement with the experiment. The sharp discrepancy for ΔH/H < 4 % is apparently explained by the high values of κ (for the absence of a stochastic change in I it is necessary that κ be much smaller than 1; when $\kappa \gg 1$ the number of oscillations may reach a total of approximately 1000).

9. CONCLUSION

The resonance exchange of energy between degrees of freedom of a charged particle takes place in any magnetic trap. However, this exchange represents a danger (in the sense of particle escape from the trap) only in systems which have "forbidden" directions for the particle velocity. In addition to traps with magnetic mirrors, this remark refers also to certain systems with compensated toroidal drift [4]. The most unfavorable condition from the point of view of resonance exchange of energy occurs in traps with "corrugated" magnetic fields [16]. In a field

‡‡ A more detailed description of the experiment is given in [15].

*** It is apparent that in the general case we can have both $\frac{1}{2}$ or 1 depending on the ratio of the quantities ρ/R and Q/Ω (cf. Section 3).

††† Special experiments to verify this theory were not carried out because at the time the calculations were initiated (fall of 1958) the experiments reported by Rodionov had already been completed and the apparatus dismantled.

of this kind, the amplitudes of the resonance harmonics for the slow oscillations (Ω_m) are considerably greater than in a field which varies monotonically.

Finally, we may note that similar resonance effects may occur in attempts to contain a plasma by means of a radio-frequency field [17, 18]. In this case there will be not an exchange of energy but a change of energy under the effect of the radio frequency oscillations.

We wish to take this opportunity to thank G. I. Budker for valuable discussions.

APPENDIX

Estimate of the Coefficients P and Q

1. We assume that $\Omega_{1m} \sim \Omega_{2m}$ and that their signs are random. We also assume that F_n is of the same order for $\frac{\omega_1}{\Omega} < n < \frac{\omega_2}{\Omega}$ and that $F_n = 0$ outside this range and that the signs of F_n are random ($\Delta\omega = \omega_2 - \omega_1$ is the interval of the change in the frequency ω). This spectral form is a good approximation for harmonic frequency modulation and can be used for estimates in other cases. Then, on the basis of the Parseval equality $|F_n| \simeq \sqrt{\Omega/\Delta\omega}$, and

$$|P_l| \simeq \frac{\sqrt{2}}{4}\sqrt{\frac{\Omega}{\Delta\omega}}\left(\sum_{m=\omega_1/\Omega}^{m=\omega_2/\Omega}\Omega_{lm}^2\right)^{1/2};$$

$$|Q_l| \simeq \sqrt{2}\,|P_l|. \qquad (I.1)$$

Applying the Parseval relation to the sum under the radical, we find that it cannot be greater than Ω^2 [cf. (2.4); $\dot{\omega}/\omega \sim \Omega$]. Assuming, furthermore, that $\Delta\omega \sim \bar{\omega}$, we have from (I.1):

$$Q/\Omega \leqslant \sqrt{\Omega/\omega}. \qquad (I.2)$$

2. If $\omega(t)$ experiences a discontinuity $\Delta^{(q)}$ in the qth derivative so that the $(q+1)$th derivative contains a δ function, direct calculation yields

$$\Omega_{1m} \to \frac{2}{\pi}\frac{\Omega\Delta^{(q)}}{\omega(2m\Omega)^q} \quad \text{for} \quad m \to \infty.$$

Substituting this expression in (I.1) we have

$$P \simeq \frac{\sqrt{2}}{\pi}\frac{\Omega\Delta^{(q)}}{(2\omega)^{q+1}}. \qquad (I.3)$$

It can be shown that the validity of (I.3) does not require that the discontinuity in $\omega(t)$ be a mathematical discontinuity character. All that is necessary is that a) the derivative $\omega(t)$ vary at any time by an amount $\Delta^{(q)}$ in a time $\ll 1/\omega$; b) that at other times the change extend over a time $\gg 1/\omega$. This is the condition under which (1) applies.

LITERATURE CITED

1. G. I. Budker, Coll.: Plasma Physics and the Problem of a Controlled Thermonuclear Reaction. 3 [in Russian] (Izd. AN SSSR, 1958) p. 3.
2. A. Bishop, Project Sherwood. USA (Mass., Addison-Wesley Publishing Company, Inc., 1958).
3. D. Judd, W. McDonald, and M. Rosenbluth, Conference on Controlled Thermonuclear Reactions (Berkeley, California, February, 1955).
4. L. A. Artsimovich, Proc. of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, 1 - Nuclear Physics [in Russian] (Atomizdat, 1959) p. 5.
5. R. Post, "Summary of UCRL pyrotron (mirror machine) program," Report No. 377, presented by U. S. to the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).
6. O. B. Firsov, Coll.: Plasma Physics and the Problem of a Controlled Thermonuclear Reaction. 3 [in Russian] (Izd. AN SSSR, 1958) p. 259.
7. R. Kulsrud, Phys. Rev. 106, 205 (1957).
8. V. M. Volosov, Doklady Akad. Nauk SSSR 121, 22 (1958).
9. A. A. Andronov, M. A. Leontovich, and L. I. Mandel'shtam, Zhur. Russ. Fiz.-Khim. Obshchestva 60, 413 (1928).
10. B. V. Chirikov, Doklady Akad. Nauk SSSR 125, No. 5 (1959).
11. N. N. Bogolyubov and Yu. A. Mitropol'skii, Asymptotic Methods in the Theory of Nonlinear Oscillations [in Russian] (Fizmatgiz, 1958).
12. F. Howard, Proc. of the CERN Conference on a 20–25 Bev Proton Synchrotron with Strong Focusing (Oct., 1953).
13. M. Kane, Ibid.
14. A. Garren, et al., Report No. 383, presented by U. S. to the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).
15. S. N. Rodionov, Atomnaya Énergiya 6, 623 (1959). ‡‡‡
16. B. B. Kadomtsev, Coll.: Plasma Physics and the Problem of a Controlled Thermonuclear Reaction. 3 [in Russian] (Izd. AN SSSR, 1958) p. 285.
17. P. Z. Sagdeev, Ibid., p. 346.
18. A. V. Gaponov and M. A. Miller, Zhur. Éksp. i Teor. Fiz. 34, 242 (1958).

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‡‡‡Original Russian pagination. See C. B. translation.

STUDIES ON CONTAMINATION OF COOLANT WATER IN THE FIRST ATOMIC ELECTRIC POWER STATION

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A study was conducted of the rate of removal of corrosion products resulting from attack of 1Kh18N9T stainless steel by the coolant water used in the First Atomic Electric Power Station. The rate of removal of corrosion products was established as a function of reactor power and blowdown of the primary loop using fresh water.

Formation of nitric acid takes place in the coolant water in response to ionizing radiations, from the nuclear reactor, as a result of oxidation of dissolved nitrogen. The chemical nature and composition of the corrosion products were investigated using the techniques of ion exchange, electrodialysis, ultrafiltration, and spectral, radiometric, and chemical analyses.

It was shown that all of the corrosion products of 1Kh18N9T stainless steel except for iron, are found in the ionic state.

Water coolants have met with widespread application in power engineering. Purity requirements imposed on coolants used in atomic power installations have become much more stringent on account of in-pile neutron activation of the contaminants.

Coolant contamination is due to impurities introduced by the feedwater and to corrosion products eroded from the surfaces of the ducting and from parts of the primary loop.

As experience acquired in the operation of the First Atomic Electric Power Station has demonstrated, the greatest hazard is presented by products of erosion of primary-loop materials, from the standpoint of the deposition of salts and the formation of scale. Among the salts deposited, we found iron, chromium, nickel, manganese, and other elements which are corrosion products of steel.

We studied the causes of corrosive attack on structural materials of the primary loop and the reasons for transport of the corrosion products, and also studied the chemical composition of solids found amoung the contaminants.

In the context of the present study, corrosion products and erosion products from the primary loop are considered together, as these processes were not studied separately.

Rate of Removal of Corrosion Products

In the practical operating experience of the First Atomic Electric Power Station, the content of solid residues in the water of the primary loop was assumed to be controlled by blowdown of the loop, using distilled water. We studied the rate of removal of corrosion products as a function of the rate of blowdown. The results are shown in Fig. 1.

It is clear from Fig. 1 that, with the reactor going at constant power, the rate of removal of corrosion products increases with rate of blowdown. To explain this phenomenon, somewhat surprising at first glance, provisions were made for constant monitoring of the physicochemical constants of the coolant.

The concentration of Cl'-, SO_4''-, NO_3'-, and CrO_4''-ions, the pH as hydrogen ion concentration, and the

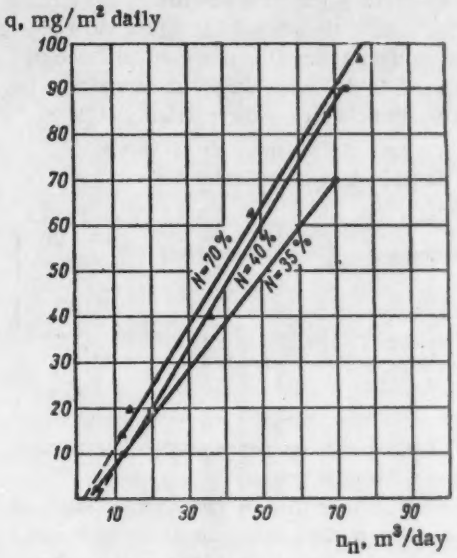

Fig. 1. Rate of removal of corrosion products as a function of blowdown of primary loop, for different reactor power levels.

amount of solids were determined in the feedwater and in the water of the primary loop. It is clear from the data obtained (see Table 1) that the pH value of the concentration of hydrogen ions is lower in the water of the primary loop than in the feedwater, while the concentration of NO_3'- and SO_4''-ions is higher. Since the concentration of Cl'- and SO_4''-ions does not vary, the lowering of pH in the water of the primary circuit may be ascribed solely to the formation of nitric acid in the circuit, since the amount of chromic acid present in the water of the primary loop can have no appreciable effect on the pH of the water.

Nitric acid forms in the coolant in response to ionizing radiations from the reactor, which affect

TABLE 1. Physicochemical Data for Water in the Atomic Electric Power Station

Feedwater						Water in primary loop					
	impurity content, mg/liter						impurity content, mg/liter				
pH	not determined	NO_3'	Cl'	SO_4''	CrO_4''	pH	not determined	NO_3'	Cl'	SO_4''	CrO_4''
6,30	0,8	0,200	0,026	0,205	0,030	5,80	1,1	0,700	0,026	0,200	0,272
6,35	0,95	0,225	0,030	0,170	0,047	5,77	1,5	0,550	0,029	0,160	0,252
6,30	1,0	0,600	0,028	0,190	0,055	5,85	1,5	1,600	0,030	0,205	0,328
6,35	0,95	0,300	Not determined			5,55	1,41	1,300	Not determined		
6,30	0,96	0,250	"	"		5,80	1,49	1,150	"	"	
6,35	0,95	0,250	"	"		5,88	1,48	0,800	"	"	

oxygen and nitrogen dissolved in the feedwater. The reaction mechanisms involved in the formation of nitric acid are described in several papers [1-6].

The fact that the nitric acid formed is to be attributed solely to the effect of ionizing radiations from the nuclear reactor may be proved by special experiments using a (electrically heated) test stand consisting of a circuit made of the same materials and having the same physical parameters as the primary loop of the atomic electric power station. In that case, the pH and the nitrate ion concentration remain practically constant (Table 2).

TABLE 2. Some of the Parameter of Water Circulated through an Electrically Heated Test Stand

Parameter	Feedwater	Water in test loop
pH	6,5	6,5
NO_3', mg/liter.	0,15	0,15
O_2, mg/liter.	8,4	1,8
Solids, mg/liter	5,8	6,0

The pH and nitrate ion concentration also remain constant at zero reactor power.

It is worthy of note that the formation of nitric acid in the water of the primary circuit requires nothing more than the mere presence of nitrogen, since the water itself contains oxygen, under the conditions of an operating reactor [7].

Nitrates are formed in the interaction between the acid and the structural materials of the loop [4]; the latter are readily swept off and transported by the flow of circulating water, and nitrates again form on the surface of the scrubbed metal while it is being attacked by nitric acid. The higher the rate of feed of make-up to the primary loop, the greater the amount of dissolved nitrogen and oxygen introduced to the circuit, and consequently the more nitric acid formed, followed by nitrates washed from the surface of the loop annulus. A portion of the acid which does not have sufficient time to attack the metal remains in the water in free form, lowering the pH. This is confirmed by the experimental data entered in Table 1. Were it not for the fact that the nitric acid formed is spent in dissolving and eating aways the materials of the primary loop, the concentration of hydrogen ions in the water would be even higher than that observed in practice. This becomes apparent from inspection of Table 3, where empirically obtained pH values for the primary-loop water and theoretically predicted values based on the concentration of nitrate ions in the coolant water are presented.

TABLE 3. pH of Water in the Atomic Electric Power Station

Feedwater		Water of primary loop		
NO_3', mg/liter	pH	NO_3, mg/liter	pH (experimental)	pH (predicted)
0,200	6,30	1,600	5,00	4,60
0,250	6,30	1,200	5,65	4,72
0,300	6,35	1,300	5,55	4,74
0,250	6,30	1,150	5,98	4,73

It is clear from the foregoing discussion that blowdown of the primary loop using nondeaerated water plays a double role in the processes of accumulation of salts in the coolant water: on the one hand, contaminants are partially removed because of dilution by addition of make-up containing a lesser amount of solids, and on the other hand, still more important, the rate of removal increases appreciably, with the amount of impurities in the coolant consequently increasing.

In order that the feedwater fulfill its immediate function, that of improving the quality of the coolant, feedwater used in atomic power installations must be carefully stripped of nitrogen. The flow plan of the loop must be engineered in such a way that admission of air into either the feedwater of the water circulated or through the primary loop is averted.

The source of coolant contaminants may be a volume compensator when it is filled with nitrogen or air. However, appropriate design techniques may succeed in sharply reducing contamination of the coolant by entrained nitrogen.

The rate of removal of corrosion products, as a function of reaction power, has been studied at various rates of

feed ranging over 4.8, 12, 50, and 71.3 cubic meters per day The results are presented in Fig. 2.

As might be expected, the rate of removal of corrosion products increased as the reactor power did, and even faster than the rate of feed. This is due to the increased yield of fixed nitrogen accompanying an increase in the intensity of neutron and gamma radiation.

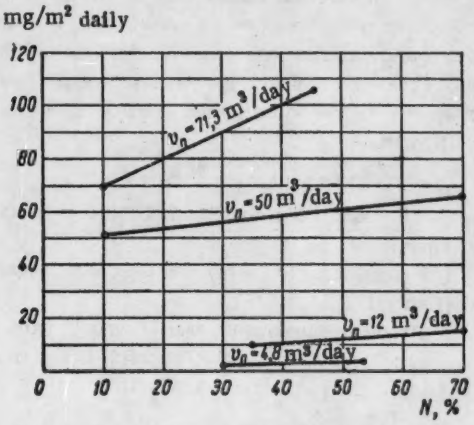

Fig. 2. Dependence of rate of removal of corrosion products on reactor power.

It was thus found that the rate at which corrosion products formed from the materials of the primary loop are washed away increases sharply as the rate of blowdown with fresh water increases. The increase in reactor power also leads to an increase in the rate of corrosion products removal.

Chemical Nature of the Contaminants in the Water Coolant

Spectral, chemical, and radiochemical analyses of the water in the primary loop of the atomic electric power station resulted in detection of the following chemical elements: sodium, calcium, magnesium, aluminum, iron, copper, nickel, cobalt, chromium, manganese, and silicon. Of these, iron, chromium, nickel, cobalt, and manganese were corrosion products of the loop materials.

The mechanism discussed above, involved in the washing away of the corrosion products, gives ground for inferring that most of the contaminants are found in the water circulating through the primary loop in ionic form.

As the primary-loop coolant water circulates through the reactor core, a part of the impurities present in the water becomes activated and converted into radioactive material; observation of the behavior of those substances in various reactions and processes had made it possible to successfully arrive at a concept of the chemical nature of the contaminants.

We employed the following techniques in studying the chemical nature of the contaminants: ion-exchange, analytical-chemical, electrodialysis, and ultrafiltration, in combination with radiochemical methods.

The study of sorption of contaminants of the water coolant by ion exchange resins provides the first picture of the chemical nature of the contaminants. Experiments were carried out over the course of several months for this purpose. Several liters of water which had been passed through a cation exchange bed and then through an anion exchange bed were sampled each month from the primary loop.

Samples were taken from the primary-loop coolant water and from the filtrates for measurement of beta decay. The components present in the coolant water and adsorbed on the ion exchange resins were determined by subsequent radiometric analysis of the decay curves. The total value of the β activity of the impurities in the coolant water of the atomic electric power station amounted to $\sim 5 \cdot 10^{-5}$ curie/liter.

Radiometric analysis showed that the initial water had six radioactive components with the following average half lives: 2.5 hr and 15 hr; 26.5, 42, and over 100 days, and ~ 5 years. The filtrate, after passing through the cation exchange bed, had three radioactive components with half lives of 2.5 hr, 26.5 and 42 days, and the filtrate passed through the anion exchange step had a single radioactive component with a half life of 42 days. Measurements of the energies of the β and γ radiations of the radioactive components in samples of water (the original water and water obtained after filtration through ion exchange beds), and radiochemical, analytical-chemical, and spectral analyses* of the solutions obtained after the ion exchange resins were regenerated showed that sodium, calcium, iron, copper, nickel, cobalt, manganese, chromium, and silicon were contained in the original coolant water.

Of the elements enumerated, sodium, calcium, nickel, copper, cobalt, and to a partial extent chromium, appeared as positively charged ions (absorbed on cation exchange resin), while silicon and chromium appeared as negatively charged ions (adsorbed on anion exchange resin), with iron being present in the form of colloidal particles.

It must be noted that a considerable portion of the iron (80-90 %) was retained by the cation exchange resin, since the latter constitutes a mechanical filter of a peculiar sort.

More precise results in the determination of the chemical nature of the coolant contaminants were provided by the method of electrodialysis, which enabled us to not only completely separate out colloids from ions, but also to determine the sign of their charges.

We used a conventional three-chamber electrodialyzer equipped with colloidal membrane. The radius of the membrane pores ranged from 1.1 mμ to 4.2 mμ, the

* Spectral analyses were performed under the supervision of Sh. I. Peizulaev.

permeability factor was $1.0-1.4 \cdot 10^{-1}$, and the membrane thickness was 0.011-0.052 cm. Using the electrodialysis technique, we were successful in determining only those elements having comparatively long-lived radioisotopes, since two to three days were required to carry out the electrodialysis procedure.

Radiometric analysis of the catholyte, anolyte, and residues in the middle cell showed that calcium and cobalt are present in the coolant water in the form of cations, chromium in the form of anions, and iron in the form of colloidal particles.

The method of ultrafiltration was employed to prove that sodium, nickel, manganese, and silicon are also present as ions in the coolant water. Ultrafiltration setups with filter pore radii of 1.4-4.2 mμ were used (for colloidal particles of 10-100 mμ diameter).

Only iron and copper were detected in the form of colloids, and these contributed 1-5 % of the total activity.

The method of adsorption on ion exchange resins was unsuccessful in establishing the true nature of the copper, probably because the pH of the medium was reduced as a result of ion exchange on cation exchange resin in the H^+-form; copper colloid is evidently dissolved and retained in the lower-lying layers of the resin under those conditions.

It was thus established that sodium, calcium, manganese, nickel, cobalt, chromium, and silicon are present in the form of ions in the coolant water, while iron and copper are present in colloidal form.

On the basis of the foregoing discussion, we may draw the conclusion that the opinion presently entertained by specialists on water treatment and water control in power installations, to the effect that corrosion products are present in the form of colloidal suspensions, may not be extended to apply to atomic power installations, where dissolved air is present in the water of the primary circuit.

In conclusion, we should like to take this opportunity to express our heartfelt thanks to A. K. Krasin for the kind attention he showed to the work, to V. V. Fomin for valuable consultations, to G. N. Ushakov and the team of co-workers in the First Atomic Electric Power Station, for their kind assistance in carrying out the investigations.

LITERATURE CITED

1. S. Ya. Pshezhetskii and M. T. Dmitriev, Atomnaya Énergiya 3, 350 (1957).†
2. J. Wright, Atomic Energy Research Establishment (Harwell, 1955) p. 157.
3. J. Wright, J. Linacre, W. Marshi, and T. Bates, Proc. Intern. Conference on the Peaceful Uses of the Atomic Energy (Geneva, 1955) (U.N., N. Y. Vol. 7, p. 658).
4. W. Primac and L. Fuchs, Nucleonics 13, 38 (1955).
5. K. Hartec and S. Dondes, Nucleonics 14, 22 (1956).
6. J. Welinsky, P. Cohen, and J. Seamon, Proc. Am. Power Conf. 18, 559 (1956).
7. T. Rockwell and P. Cohen, Water Chemistry of the PWR Reactor, Geneva 1955 Conference P/536. Vol. 9, p. 423.

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ANISOTROPY OF THE PROCESS OF FISSION OF U^{238} BY 14 MEV NEUTRONS

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The double ionization-chamber method is used to study the angular distribution of the fragments produced by the fission of U^{238} by neutrons with energy 14.4 Mev. It is found that to an accuracy of 3 percent the angular distributions of the light and heavy fragments are symmetric with respect to the direction perpendicular to the neutron beam. Furthermore, it is shown that the directions of emergence of the light and heavy fragment are equally privileged, both in symmetric and in asymmetric fissions. It is found that for ratios of the masses of the fragments less than 1.7-1.8, the angular anisotropy increases with increase of the asymmetry of the masses. The results are discussed from the point of view of the statistical theory of V. M. Strutinskii.

A previous paper [1] gave an account of the first results of a study of the anisotropy of the fission process, made with a double ionization chamber. The present paper presents the results of further studies and describes the experimental method.

METHODS

By simultaneous measurements of the kinetic energies of the two corresponding fragments, the mass distribution of the fragments was determined at various angles with the direction of the neutrons that produced the fissions. A diagram of the experimental arrangement is shown in Fig. 1.

The energies of the fragments were measured by means of a double ionization chamber, which consists of two plane-parallel chambers with screening grids and a common cathode. The design of the chamber and grid was calculated according to the method described in [2]. The efficiency of the grid shielding was taken to be 96%. In the central part of the cathode electrode, over the area of circle diameter 25 mm, 3500 holes were drilled; these formed the collimator. The holes, 0.3 mm in diameter, were drilled normal to the plane of the collimator. On the collimator was placed a target of natural uranium of thickness 50 g/cm^2; this was prepared by evaporation in vacuum of uranium oxides onto a collodion film of the same thickness, which was transparent to the fission fragments. To check the stability of the functioning of the apparatus, Po^{210} α-ray sources were placed on both sides of the cathode. The chamber had a calcium purifier and was filled with the gas mixture (97% A + 3% CO_2) to a pressure of 900 mm Hg.

After amplification, the pulses from the chamber were fed to the deflecting plates of a type 18LO-47 two-beam oscilloscope tube. Signals from the coincidence circuit were applied to the modulating electrodes of the tube, so that only those pulses were registered that came from fragments produced in the same act of fission. The registration was accomplished by photographing the luminous points that appeared on the oscilloscope screen on motion-picture film of high sensitivity. It was verified that the apparatus was linear over the entire range of pulses studied, and was stable in time.

The chamber was exposed to a source of neutrons of energy 14.4 Mev, which came from the reaction $T(d,n)He^4$ in a tritium-zirconium target bombarded by deuterons accelerated to 180 kev. The energy distribution of the collimated fission fragments was taken with the camera in two different positions relative to the neutron beam. In the "0°" position the direction of incidence of the neutrons coincided with the axis of the canals of the collimator. In the "90°" position the neutron beam was incident at an angle of 84° with the axis of the collimator canals. In both cases the neutron source was at a distance of 15 cm from the center of the fissionable layer of diameter 2.5 cm. The maximum angle between the direction of emission of the fragments and the axis of the canal was 9°. Thus in the "0°" position the maximum angle between the directions of the neutrons causing the fission and the fragments registered did not exceed 15°. In the "90°" position the minimum angle between these directions was not smaller than 75°.

The energy of the fission fragment emitted into the side of the chamber in which the uranium target was (hereafter we call this chamber A) was determined by comparing the pulses from the fragments with pulses from the α particles of U^{238}. The energy of the fragment that passed through the collodion film and a collimator canal into the other side of the chamber (chamber B) differs from that of an identical fragment emitted into chamber A by the amount of the losses in the film and the collimator. These losses were determined by comparing the spectra of the fragments in chambers A and B in the case of observation of fissions at angle 90° with the incident neutron beam. The measured energy values were corrected for losses by nonionizing processes [3] and for the motion of the center of mass. The weak dependence of these corrections on the energy of the fragment was not taken into account. Also neglected were the loss of energy of the fragment in the layer of fissionable material (which was less than 1 Mev)

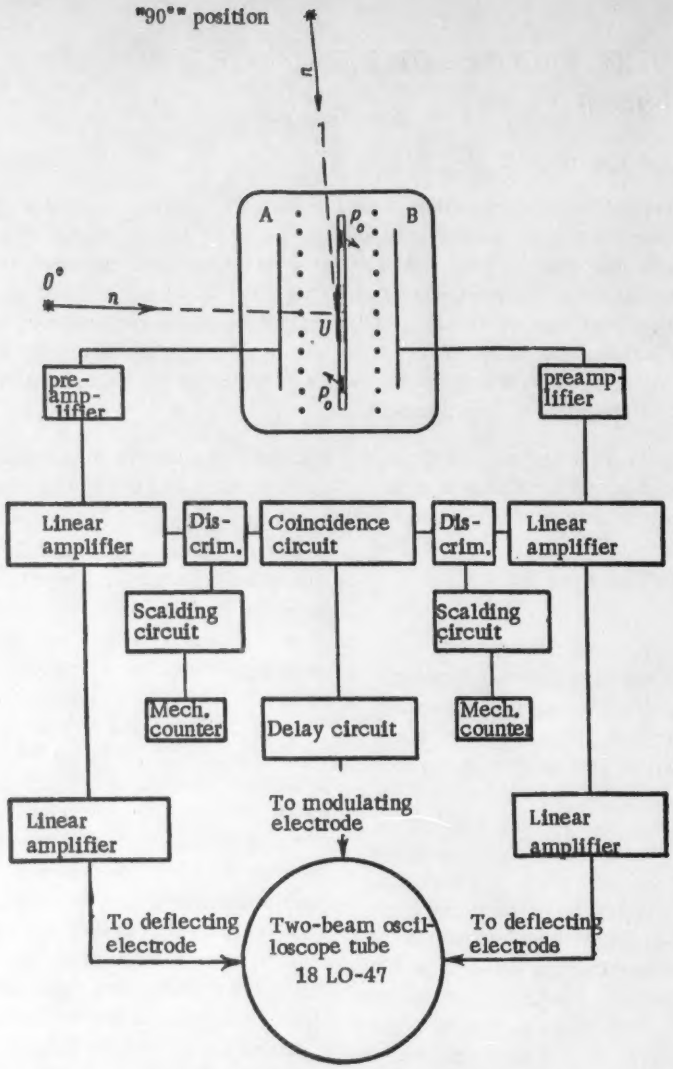

Fig. 1. Diagram of the experimental arrangement.

and the energy loss in emission of neutrons. Estimates showed that the errors caused by these simplifications could not have any important effect on the results.

RESULTS

The two positions were interchanged periodically, and about 2000 fissions were registered in each position.

The large number of acts of fission registered made it possible to study the question of the equal probabilities of the directions of emission of the light and heavy groups of fragments in various regions of the spectrum of fragment masses. In accordance with the mass ratios of the fragments, all the cases of fission were arbitrarily divided into three groups, corresponding to almost symmetrical fission (1.0-1.3), asymmetrical fission (1.3-1.5), and strongly asymmetrical fission (1.5 and more). For each group the fraction of cases was determined in which the light fragment emerged into chamber A, out of the total number of fissions registered in the direction parallel to the beam. The deviation of this quantity from the value characteristic of an isotropic distribution (50 percent) leads to a conclusion about the extent to which the probabilities are equal for the possible directions of emission of the fragment – forward and backward relative to the incident neutrons. As a check, the fraction of fissions with emergence of the light fragment into chamber A was also determined in the case of fission of the nucleus in the direction perpendicular to the beam. The results of the measurements for the separate groups and for the total spectrum (mass ratios 1 and more) are shown in the table.

It can be seen from the table that within experimental error there is no case in which the fraction of fissions with emission of the light fragment into chamber A is different from 50%. Consequently, to an accuracy of

10 percent for the separate groups and to 3 percent for the total spectrum, the angular distribution of the light fragments is symmetrical relative to 90° and does not differ from the angular distribution of the heavy fragments.

Ratio of Number of Cases of Emergence of the Light Fragment into Chamber A to Total Number of Fissions, Percent

Ratio of masses of fragments	Fission in direction perpendicular to beam	Fission in direction parallel to beam
1,0—1,3	45±3*	46±3*
1,3—1,5	50±3	53±3
1,5 and more	54±3	49±3
1,0 and more	50±2	49±2

*Here, and hereafter, the errors shown are the statistical errors.

Figure 2 shows the distribution curves of the masses of the fragments for fissions in the directions parallel and perpendicular to the neutron beam. It can be seen that the distribution of the fragments depends on the direction of the fission. The proportion of asymmetric splittings is larger for fissions along the neutron beam than for those in the perpendicular direction. This change in the mass distribution means that there is a dependence of the anisotropy on the ratio of the masses of the fragments; this is shown on the same diagram (it is assumed that the fission cross section at angle 0° is 40 percent larger than that at angle 90° [4]). In the region where the statistical accuracy of the experimental data is satisfactory (solid curve), the anisotropy increases with increase of the asymmetry, reaching its maximum value in the neighborhood of 1.7-1.8.

DISCUSSION

The conclusion about the equal probabilities of the directions of emission of the light and heavy fragments is in agreement with our preliminary communication [1] and with the results of work by Cohen and collaborators [5], which was done by a radiochemical method with 22 Mev protons. The small difference in the ionization spectra of the fragments at angles 0° and 90° that was observed by Brolley, Dickinson, and Henkel in the case of the fission of Np^{237} by 14.3 Mev neutrons was evidently caused not by unequal probabilities for the light and heavy fission fragments, but by unequal probabilities of different modes of fission. This latter effect manifests itself in the larger anisotropy of the asymmetric modes of fission, as is shown in Fig. 2. An increase of the anisotropy with increase of the mass ratio of the fragments has also been observed by Fairhall, Halpern, and Winhold [6] in the case of fission of Th^{232} by gamma rays with a continuous spectrum with maximum energy 16 Mev, and by Cohen et al. [5] in the fission of Th^{232}, U^{233}, U^{235}, and U^{238} by 22 Mev protons. The observation of such a connection between the angular and mass asymmetries, also in the case of fission caused by neutrons, emphasizes the generality of the phenomenon.

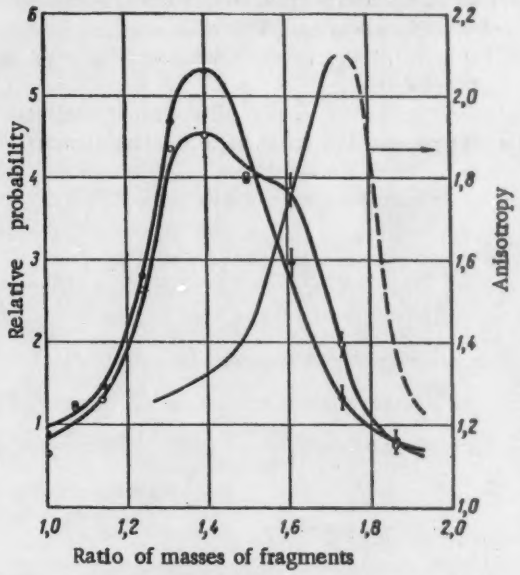

Fig. 2. Distribution of masses of fragments: ○) for fissions at angle 0°; ●) for fissions at angle 90° with neutron beam. The distributions are normalized to the same total number of fissions at each angle.

There have so far been only scattered attempts to explain the large anisotropy of asymmetrical fission [7, 8]. The statistical theory of the angular distribution of fission fragments proposed by V. M. Strutinskii includes the assumption of a dependence of the angular asymmetry on the moment of inertia of the fragments around the axis connecting their centers. The increase of the anisotropy for asymmetrical fission is then explained by the smaller values of the moment of inertia of the nuclei, close to magic nuclei, that are produced in this case. For strongly asymmetrical fission, when the fragments are far from magic nuclei, there may be a fall of the anisotropy. It is possible that this sort of effect has indeed been observed in the present work (dashed curve in Fig. 2), but the statistical accuracy of the results does not allow us to draw a definite conclusion. This last point calls for further study.

In conclusion the authors express their gratitude to M. I. Kuznetsov, who helped with building the pulse analyzer, and to all the group operating the accelerator.

LITERATURE CITED

1. A. N. Protopopov and V. P. Éismont, Atomnaya Énergiya 4, 194 (1958).*
2. O. Buneman, T. Cranshaw, and J. Harvey, Canad. J. Research 27A, 191 (1949).
3. H. Smitt and R. Leachman, Phys. Rev. 102, 183 (1956).

4. J. Brolley, W. Dickinson, and R. Henkel, Phys. Rev. 99, 159 (1955); R. Henkel and J. Brolley, Phys. 103 1292 (1956).
5. B. Cohen, B. Ferrell-Bryan, D. Coombe, and M. Hullings, Phys. Rev. 98, 685 (1955).
6. A. Fairhall, I. Halpern, and E. Winhold, Phys. Rev. 94, 733 (1954).
7. A. Bohr, "On the theory of nuclear fission," Report No. 911 presented by Denmark at the International Conference on the Peaceful Use of Atomic Energy (Geneva, 1955).
8. V. M. Strutinskii, Atomnaya Énergiya 2, 508 (1957).*

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HIGH-ENERGY PHYSICS

(A Survey of the Materials Presented at the Eighth International Conference on High-Energy Physics)

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We give here a brief summary of the material presented at the Eighth International Conference on High-Energy Physics. At this conference there were discussions of the results of studies of the interactions of mesons, nucleons, and strange particles at high energies, and of the weak interactions between particles. There was emphasis on the advances achieved in the study of the weak interactions.

In connection with this survey of the material of the conference, we discuss the achievements of the last few years in various branches of elementary-particle physics.

The Eighth International Conference on High-Energy Physics took place in Geneva from June 29 to July 5, 1958. A difference from previous conferences was that as a rule reports were not given on individual researches. All of the material presented at the conference was summarized in the survey reports: "Structure of the Nucleon" (experiment, Panofsky; theory, Drell); "Interaction between Nucleons and π Mesons, Photons, Nucleons, and Antinucleons" (experiment, Puppi and Piccioni; theory, Chew); "Production of Strange Particles" (experiment, Steinberger; theory, Gell-Mann); "Interactions of Strange Particles" (experiment, Kaplon; theory, Dalitz); "Weak Interactions, Leptonic Decays" (experiment, Goldhaber; theory, Michel); "Weak Interactions, Nonleptonic Decays" (experiment, Glaser; theory, Treiman).

In addition, two sessions of the conference were devoted to the discussion of fundamental theoretical problems.

In view of the enormous number of researches whose results were discussed at the conference, we cannot consider them all, and shall confine ourselves to the main points.

Have New Particles Been Found? The past year did not bring great successes in the discovery of new particles. All of the elementary particles known at the present time are shown in the table. The first case of the observation of an anti-Λ hyperon was reported at the conference.* It is now the turn for the discovery of the antihyperons $\bar{\Sigma}$-, $\bar{\Xi}$, whose existence is predicted by theoretical physicists with absolute assurance. An important verification of the present systematics of elementary particles would be the discovery of the neutral cascade particle Ξ^0. One case was reported at the conference in which a decay was observed that was very much like the decay of a Ξ^0 particle.†

Attempts of a number of foreign scientists to discover a particle with mass equal to 500 electron masses, whose existence has been asserted by Alikhanyan and his coworkers, have so far given negative results.

The Fundamental Properties of Particles. Analyses of the decay of hyperons, carried out mainly by the groups headed by Alvarez, Steinberger, and Glaser, have established that the spins of the Λ and Σ hyperons are evidently equal to $\frac{1}{2}$, and that the spin of the K mesons is zero. The parities of K mesons and hyperons have not been determined, although there are a number of proposals as to how they can be found.

The Interactions Between Particles. The greatest attention was given to the interactions between the elementary particles. Four types of interactions between them are known: gravitational, electromagnetic, strong, and weak interactions.

Weak Interactions

In the past year very great advances have been achieved in the study of the weak interactions. Attention was called to them in 1956, when, as the result of the studies initiated by Lee and Yang, parity nonconservation in the weak interactions was discovered.

As is well known, the weak interactions cause the following processes: β decay, the decay of μ mesons, and the decays of π and K mesons and hyperons. The decays of K mesons and hyperons (or of the strange particles, as they are sometimes called) are divided into two large groups: leptonic decays (similar to β decay), and nonleptonic decays. Leptonic decays are necessarily accompanied by the emission of leptons (electron or μ meson, and neutrino). Examples of nonleptonic decays are: $K \to 2\pi$ (the so-called θ decay), $K \to 3\pi$ (the so-called τ decay), $\Lambda \to p + \pi$, etc.

Parity Nonconservation. To begin with it was found that parity is not conserved in β decay and in the decays $\pi \to \mu + \nu$ and $\mu \to e + \nu + \bar{\nu}$. It has now been established that there is parity nonconservation also in other decay processes: $K \to \mu + \nu$, $\Lambda \to p + \pi^-$, $\Sigma \to n + \pi$. Thus, it can

* Very recently a new case of the observation of this particle has become known to us. We denote antiparticles throughout by a bar over the notation for the particle; for example, $\bar{\Lambda}$ means an anti-Λ hyperon.

† Recently, information has become available about the discovery of Ξ^0 by a group of scientists at the University of California headed by L. Alvarez.

Table of Elementary Particles

Particle	Spin	Mas, Mev	Difference of masses, Mev	Lifetime τ, sec
Photon	1	0	—	stable
Leptons				
ν, $\bar{\nu}$	1/2	0	—	stable
e^-, e^+	1/2	0,510976	—	stable
μ^-, μ^+	1/2	$105,70 \pm 0,06$	—	$(2,22 \pm 0,02) \cdot 10^{-6}$
Mesons				
π^+, π^-	0	$139,63 \pm 0,06$	4,6	$(2,56 \pm 0,08) \cdot 10^{-8}$
π^0	0	$135,04 \pm 0,16$		$4 \cdot 10^{-16}$
K^+, K^-	0	$494,0 \pm 0,2$	0,4±1,8	$(1,224 \pm 0,013) \cdot 10^{-8}$
K^0	0	$494,4 \pm 1,8$		$K_1^0 \rightarrow \left(0,99^{+0,08}_{-0,06}\right) \cdot 10^{-10}$
				$K_2^0 \rightarrow \left(9,0^{+3,5}_{-2,3}\right) \cdot 10^{-8}$
Baryons				
p, $\bar{p}$	1/2	$938,213 \pm 0,01$	—	stable
n, $\bar{n}$	1/2	$939,506 \pm 0,01$	—	$(1,011 \pm 0,026) \cdot 10^{-3}$
Λ, $\bar{\Lambda}$	1/2	$1115,2 \pm 0,14$	—	$\left(2,60^{+0,16}_{-0,14}\right) \cdot 10^{-10}$
Σ^+	1/2	$1189,4 \pm 0,25$	7,1±0,4	$\left(0,75^{+0,10}_{-0,09}\right) \cdot 10^{-10}$
Σ^-	1/2	$1196,5 \pm 0,5$	$6,0^{+1,4}_{-0,9}$	$\left(1,72^{+0,17}_{-0,10}\right) \cdot 10^{-10}$
Σ^0	1/2	$1190,5^{+0,9}_{-1,4}$		$< 0,1 \cdot 10^{-10}$
Ξ^-	?	$1320,4 \pm 2,2$	—	$(4,6 < \tau < 200) \cdot 10^{-10}$

be regarded as proved that there is parity nonconservation in all cases of weak interactions leading to decays of particles.

Nonconservation of Charge Parity. At the same time, it was proved that the weak interactions do not conserve the charge parity, which characterizes the properties of a system of elementary particles with respect to the replacement of all particles by their antiparticles.

Is the Combined Parity Conserved? Landau put forward the hypothesis that although the spatial and charge parities are not conserved in weak interactions, nevertheless there must be conservation of the combined parity, which is the product of the spatial and charge parities. At present there are no experimental data that contradict this hypothesis. The conservation of combined parity has been most accurately checked in β decay. On the basis of the data on the β decay of the neutron, the conservation of combined parity has been proved to an accuracy of about 20 percent. Using data on the β decay of RaE, Alikhanov and his co-workers have proved the conservation of combined parity with an accuracy of about 5 percent.

The Longitudinal Neutrino. In 1956, Salam, Landau, and Lee and Yang independently proposed the hypothesis that the neutrino and antineutrino are always completely polarized along the direction of motion. Furthermore, one of these particles must be polarized in the direction of motion, and the other opposite to the direction of motion. A large number of different experiments confirm this hypothesis.

It still remained unclear, however, as to which of the two particles was polarized in the direction of motion and which was oppositely polarized. This question was settled by an ingenious experiment of Goldhaber and his co-workers, who proved that the neutrino is polarized opposite to its direction of motion. As is well known, the wave function of a particle with spin $\frac{1}{2}$ has four components. From the fact that the neutrino is always polarized longitudinally it follows that only two of the four components of the wave function that describes the neutrino are different from zero. From this we get another name for the longitudinal neutrino: the two-component neutrino.

Thus, in all the weak interactions, the neutrino enters only through two components. Since the neutrino does not take part in any other interactions and its mass is zero, it always remains completely longitudinally polarized.

The "Two-Component" Electron. Experiments made to measure the polarization of the electrons (Alikhanov, Nikitin, Frauenfelder, and others) and the electron-neutrino correlation (Allen, Burgov, and others) have shown that not only the neutrino but also the electron enter through only two components, and, moreover, these are

the same pair of components as for the neutrino. Since, however, unlike the neutrino, the electron does not have zero mass, the electrons emitted in β decay are not completely longitudinally polarized. The degree of their longitudinal polarization is v/c, where v is the speed on the electron and c is that of light.

Experiments on the electron-neutrino correlation had given contradictory resusts. At the present time the contradictions in these experiments have been essentially cleared up.

The Vector and Axial Vector Interaction Types. The fact that the electron and neutrino enter the β-decay interaction through the same components means that the interaction types realized in the β decay are the vector and axial vector forms. These forms, denoted by the letters V and A, are two of the five types usually considered. The three other types – the scalar, pseudoscalar, and tensor – are denoted by the letters S, P, and T, respectively. Clearly it can be regarded as experimentally established that in β decay the admixture of the S, P, or T interaction does not exceed 10 to 20%.

The Universal Weak Interaction. The β-decay data that have been mentioned have been a brilliant confirmation of a bold hypothesis put forward in the autumn of 1957 by Marshak and Sudarshan and by Gell-Mann and Feynman. According to this hypothesis all the weak interactions come from interactions of fermions in which all particles and antiparticles enter through only two components. This simple picture becomes more complicated when one takes into account the fact that some of the particles can also interact through strong interactions

The Decay of the Neutron. Thus, if there were no strong interaction between protons and neutrons, it would follow from the theory of the universal weak interaction that the ratio of the constants for the axial-vector and vector types should be −1 in the β decay of the neutron. The experiments of Spivak and his co-workers, who measured the lifetime of the neutron with high accuracy ($T_{\frac{1}{2}}$ = 11.7 ± 0.3 min), and studies of the decay of polarized neutrons (Novey, Telegdi, and co-workers), give for this ratio the value 1.20 ± 0.04.

The Decay of the μ Meson. For the decay of the μ meson the predictions of the theory of the universal interaction are in good agreement with experiment. The shape of the spectrum and the polarization of the electrons produced in this decay agree with the theory. The shape of the electron spectrum is usually characterized by the Michel parameter ρ. The theory predicts that ρ = 0.75. The latest experiments give ρ_{exp} = = 0.736 ± 0.022. The positrons from μ^+ decay are polarized along the direction of motion, in agreement with the theory. Since the μ^+ meson is the antiparticle of the μ^- meson, comparison of the properties of the μ^+ and μ^- decays gives the possibility of a direct test of charge parity.

A very clear experimental proof of the nonconservation of charge parity was reported at the conference. The polarization of the electrons from the decay of μ^- has the opposite sign from that of the positrons from the decay of μ^+ (Culligan, Crowe).

The Decay of the π Meson. At the time of the opening of the conference the data on the decay of the π meson were in serious contradiction with the theory of the universal weak interaction. The decay of the π meson into a μ meson and a neutron ($\pi^+ \to \mu^+ + \nu$) is well known. On the other hand, experiments conducted for this special purpose had not revealed the decay of the π^+ meson into a positron and a neutrino, $\pi^+ \to e^+ + \nu$. The theory of the universal weak interaction gives for the ratio of the probabilities of these decays a value close to 1/8000. The problem of the $\pi - e$ decay was very actively discussed at the conference. Several of possible theoretical explanations for the absence of this decay were put forward. It was only after the conference was over that notes appeared stating that the $\pi - e$ decay had finally been discovered, and that its probability is close to that theoretically predicted (the Steinberger group and the CERN group).

A matter of great importance for the study of the weak interactions is that of testing the conservation of leptons. No experiments made up to the present time contradict this conservation law. For a direct experimental test of the conservation of the number of leptons it is necessary to determine the direction of the spin of the μ meson from $\pi - \mu$ decay.

The Decay of Strange Particles. The data on the decays of strange particles are in qualitative agreement with the predictions of the theory of the universal weak interaction. This is true in particular of the data on the sign of the polarization of the protons from the decay of Λ particles ($\Lambda \to p + \pi^-$), obtained at the Massachusetts Institute of Technology, and of the data on the decay of the μ mesons from the decay of K mesons ($K \to \mu + \nu$, $\mu \to e + \nu + \bar{\nu}$). The only fact in contradiction with the theory is the absence of leptonic decays of hyperons, such as $\Lambda \to p + e^- + \nu$, $\Sigma \to n + e + \nu$. The total number of observed hyperon decays is close to 1500. The theory of the universal weak interaction predicts that in such a number of decays of hyperons there should be some tens of leptonic decays. Up to now, the experimenters have not found a single reliable case of the leptonic decay of a hyperon. So far, however, we do not have to speak of a serious contradiction in this matter, since both the theoretical predictions and the experimental data on leptonic decays of hyperons may perhaps change. We remark that the theoretical predictions are not unambigous, since they depend in an essential way on assumptions about the character of the strong interaction between nucleons and hyperons.

The Capture of μ Mesons by Nucleons. For further tests of the theory of the universal weak interaction it is necessary to carry out a number of experiments. In particular, we need to measure the polarization of the μ mesons produced by the decay of μ mesons. The

process of $\pi - e$ decay requires further study, and leptonic decays of hyperons must be looked for. A process of special interest is the capture of μ mesons by protons ($\mu^- + p \rightarrow n + \nu$). It is well known that the probability of this process involves the interaction constant to the same power as does ordinary β decay. There are, however, no accurate experimental data on the capture process. To test the universal weak interaction it is necessary to carry through a whole program of investigations needed to establish the type of interaction, similar to the studies that have been made for the β decay. A result of importance for such studies is that of Ignatenko et al., who observed the complete depolarization of the μ mesons in liquid hydrogen; this had been theoretically predicted by Zel'dovich and Gershtein.

"Weak Magnetism". We have already mentioned the fact that the properties of the weak interaction are changed by effects of strong interactions. The same is true of the electromagnetic interaction. For example, it is well known that because of the presence of the so-called cloud of virtual π mesons surrounding a proton or a neutron there are changes of the magnetic properties of these particles, and anomalous magnetic moments arise. It is no less well known, however, that the total charge of the proton or neutron is not changed by this; for the proton, it is equal to the charge of the positron, which has no strong interaction, and for the neutron it is zero. The question arises: does not the weak interaction have the same property, that is, is there not an analogy between the weak β-decay interaction and the electromagnetic interaction? The suggestion by Feynman and Gell-Mann that such an analogy may exist was stimulated by the remarkable precision with which the decay constant of the μ meson agrees with the vector-type constant of β decay. This agreement suggests that the constant for the vector interaction, like the electric charge, is not affected by the strong interaction. As early as 1955, Gershtein and Zel'dovich had called attention to such a possibility.

The analogy between the vector β-decay interaction and the electromagnetic interaction was used by Gell-Mann for the calculation of corrections to allowed β-ray spectra caused by "weak magnetism." He succeeded in expressing these corrections in terms of quantities characterizing ordinary electromagnetic transitions in nuclei.‡ Since the constant of the axial-vector interaction is larger by a factor 1.2 than that of the vector interaction, on the basis of the theory of the universal weak interaction we must conclude that, unlike the constant characterizing the vector interaction, the constant of the axial-vector interaction does not remain unchanged, just as in the analogous case the magnetic moments of proton and neutron are altered. This evidently applies also to the weak interactions of strange particles.

The Rule $|\Delta S| = 1$ and the Mass Difference of Neutral K Mesons. In all known nonleptonic decays of strange particles the change of the strangeness S is ± 1. An experimental result supporting this rule was reported at the conference. Surprising as it may be, the check was obtained not by a study of the decays of strange particles, but by measurement of the mass difference of the two types of neutral K mesons, K_1^0 and K_2^0. The point is that if only weak processes with $|\Delta S| = 1$ are allowed, the difference of the masses of K_1^0 and K_2^0 mesons must be approximately 10^{11} times smaller than the mass of the electron. If processes with $|\Delta S| = 2$ are allowed, the mass difference must be about 10^{-6} electron mass. A study of the transition of K mesons into K^0 mesons in a beam of neutral K mesons (the Gell-Mann–Pais–Piccioni process), in experiments which are not yet completed (Massachusetts Institute of Technology), has shown that the difference of the masses of K_1^0 and K_2^0 mesons is about 10^{-11} electron mass. Thus the rule $|\Delta S| = 1$ has been confirmed. In itself, the "weighing" of a mass difference of neutral unstable particles with such precision ($10^{-11} m_e = 10^{-40}$ g) is a unique achievement.

The Rule $\Delta T = \frac{1}{2}$. In connection with the study of nonleptonic decays of strange particles there have been discussions for the last few years on the problem of the accompanying changes of the isotopic spin. There has been especially widespread discussion of the hypothesis that the change of the isotopic spin T is $\frac{1}{2}$. The rule $\Delta T = \frac{1}{2}$ leads to a number of relations between the probabilities of various decays of hyperons and K mesons. For example, it follows from this rule that the ratio of the probabilities of the decays $\Lambda \rightarrow p + \pi^+$ and $\Lambda \rightarrow n + \pi^0$ is 2. Good agreement with this rule is found in the experimentally determined ratio of the probabilities of the decays $K^+ \rightarrow 2\pi^+ + \pi^-$ and $K^+ \rightarrow \pi^+ + 2\pi^0$. It is also not contradicted by the data on Σ hyperons. Essentially, only one case contradicts the rule $\Delta T = \frac{1}{2}$; this is the decay of the K_1^0 meson: $K_1^0 \rightarrow 2\pi^0$ and $K_1^0 \rightarrow \pi^+ + \pi^-$. The number of decays of the former type found experimentally is considerably smaller than would follow from the theory. Nevertheless further testing of the $\Delta T = \frac{1}{2}$ rule is desirable, in particular in decays of K_2^0 mesons.

Let us now pass on to the other two types of interactions mentioned at the beginning of this review: electromagnetic interactions and strong interactions.

The Electromagnetic Interactions

An important question is whether or not the character of the ordinary electromagnetic interaction between particles changes when they are extremely close together. An answer to this question can be obtained from studies of the scattering of electrons by protons (these experiments are being done by Hofstadter at Stanford, up to electron

‡ On the basis of analogous considerations it has been predicted that there is an angular dependence of the $\beta - \gamma$ correlation in allowed transitions. It has recently been reported that this has been observed experimentally, and that the effect is close to the theoretically predicted value.

energy 600 Mev), and of the scattering of electrons by electrons and the production of electron-position pairs with large momentum transfers (Panofsky).

The magnetic moment of the μ meson is a quantity that is very sensitive to possible changes of the electromagnetic interaction at small distances. The most accurate experimental data on the gyromagnetic ratio of the μ meson, $g_\mu^{exp} = 2\,(1.0015 \pm 0.0006)$, is to be compared with the theoretical value $g_\mu^{theor} = 2 \cdot 1.0012$. The body of experimental data indicates that the laws of electrodynamics evidently do not change at distances larger than $3 \cdot 10^{-14}$ cm. (Somewhat more exactly: $3 \cdot 10^{-14}$ cm for the photon propagation function, $8 \cdot 10^{-14}$ cm for the electron propagation function.

It is interesting to note that further improvements in the value of such a property of a particle as g_μ can give the same information as experiments with electrons of enormous energies.

The Strong Interactions

The strong interactions of elementary particles are one of the most complicated problems on which the physicists of various countries have been working for the past several years. The nature of the strong interactions of π mesons and nucleons has a very strong effect on the strong interactions of other particles. The complexity of the strong interactions calls for a great number of investigations with various particles at various energies. Moreover, we do not have any sort of satisfactory theory of these phenomena, and must limit ourselves to a phenomenological analysis of the experiments, i.e., to an analysis based only on the conservation laws. This analysis gives information as to the parts played in the interaction by states with different values of the angular momentum l. Its completion also requires experiments with beams of polarized particles.

The discovery of parity nonconservation in the weak interactions has led physicists to carry out investigations to determine more rigorously to what accuracy there is conservation of space and time parities, and also of isotopic spin, in the strong interactions.

The law of conservation of isotopic spin has been verified up to energies of 300 Mev for the $\pi - N$ interaction, and has been verified in specially conducted experiments on the production of neutral mesons in n—p collisions at 600 Mev (V. Dzhelepov and co-workers). No deviations from conservation of the space and time paririties have been found in the strong interactions of ordinary particles.

The Structure of Nucleons. As has already been mentioned, because of the strong interactions of nucleons they are surrounded by peculiar clouds of strongly interacting particles. Important information can be obtained about the properties of these clouds by studying the scattering of electrons by nucleons. Such experiments have been carried on for several years at the Stanford linear accelerator. The energy of the scattered electrons has now been carried up to 600 Mev. The structure of the clouds surrounding nucleons is usually spoken of as the form factors of nucleons. The structure of each of the nucleons is characterized by two form factors: electric and magnetic; the former describes the distribution of electric charges, the latter, that of currents. It has been found that the electric and magnetic form factors of the proton are roughly equal to each other (with accuracy about 20 percent), and correspond to distributions with rms radius $8 \cdot 10^{-14}$ cm. The magnetic formfactor of the neutron has these same characteristics. The distribution of charges in the neutron differs surprisingly from those just described, and its rms radius is smaller than 10^{-14} cm. A satisfactory theoretical explanation of this anomaly has not been given.

The Interaction of Nucleons with Nucleons. In the range of energies up to 700 Mev an important contribution has been made by the studies made with the synchrotron at the Joint Institute of Nuclear Studies. To the data obtained earlier on the interaction between nuclei there has been added information on the depolarization in p—p scattering and on the polarization in n—p scattering, and also the results of the number of studies of the mechanism of production of mesons in collisions between nucleons.

There was a very interesting communication about measurements of the correlation of the polarization in p—p scattering (from Liverpool), which have made it possible to determine (for just one value the energy!) the relative contributions of the interaction cross sections with different mutual orientations of the spins of the particles. There were also discussions of the results of a number of other very interesting experiment, for example a study of the production of mesons by polarized protons over a wide range of energies (Soroko et al.), which has provided data on the production of mesons in the d state. An enormous amount of work still remains however, before we can have a complete analysis of the effects that occur in nucleon-nucleon collisions at various energies.

The conference heard reports on data obtained by a large group of workers, among them Wang Shu-fen (China), Danysz (Poland), Dalkhazhav (Mongolia), Vishki (Romania), and Markov (Bulgaria), on the interaction of protons accelerated to 9 Bev by the synchrophasotron at the Joint Institute of Nuclear Studies with nucleons and nuclei; this work gave determinations of the cross sections for elastic scattering and for inelastic processes. It was found that the number of particles produced increases with the energy. An estimate was obtained of the energy that goes into the production of mesons. Data were obtained on the production of strange particles.

The data on the elastic scattering at such high energies are being analyzed from the point of view of diffraction scattering (Blokhintsev et al.). The authors hope to obtain information on the structure of

the proton from the study of diffraction scattering.

Thus,a beginning has been made on the study of the interactions of nucleons at energies that previously were unattainable under laboratory conditions.

There was particular interest in a new approach to the analysis of experimental data which was proposed by Chew. On the basis of very general analyticity properties of the scattering amplitude, and of the fact that the present theory can give predictions for phenomena occurring at relatively large distances, Chew indicated a method by which he was able to determine the meson-nucleon scattering constant from experimental data on the scattering of nucleons by nucleons.

The further development of this method will lead to the possibility of an experimental test of the foundations of quantum field theory, and of the determination of such fundamental quantities as the constants of the meson-meson and K-meson-hyperon interactions.

Antinucleons. After the discovery of the antiproton and antineutron and the determination of the properties of the antiproton that are predicted by the Dirac theory, a beginning has been made on the detailed study of the interaction of antinucleons with nucleons and nuclei. The first thing to attract attention was the extreme largeness of the cross sections for inelastic processes and the annihilation of antiprotons. It seemed to many that another mystery was concealed here. A more detailed analysis has made it possible to believe that the marked difference between the nucleon-nucleon and antinucleon-nucleon interactions at energies up to 300 Mev is not surprising and is due to the fact that in the latter case there is conversion of nucleon-antinucleon pairs into mesons. Still more detailed calculations, some of which cannot be regarded as reliable, lead to complete agreement with the experimental data.

Further studies with antinucleons at considerably higher energies will be of great interest.

The Interaction of π Mesons with Nucleons. The interaction of π mesons with nucleons is being studied at energies up to 5 Bev. The elastic scattering of mesons by nucleons is being studied and analyzed with particular care. In the energy range from 60 to 400 Mev the fundamental data had been obtained earlier. There were discussions at the conference of new and more precise data for quite small energies (20 to 40 Mev). The previous data for such energies allowed the existence of an additional neutral particle—a π_0^0 meson with isotopic spin 1. Although this question remains open, arguments against the existence of such a particle were presented at the conference.

The angular distributions of the elastically scattered π mesons in the range of energies up to 500 Mev are analyzed in terms of phase shifts. Earlier data could be analyzed by using the lower s and p states ($l = 0,1$). A detailed analysis of the new data, among which we may note the first results on the polarization of recoil nucleons, gave more reliable information on the interaction of π mesons with nucleons in the d state.

Study and preliminary analysis of the total cross-sections of the $\pi-N$ interaction has made it possible to form hypotheses about the existence,in addition to the well resonance at about 300 Mev,of further resonances at higher energies. Indications of the existence of such resonances have been obtained from the study of the photoproduction of π mesons.

The Interaction of γ-Ray Quanta with Nucleons. The process of photoproduction of π mesons is beginning to be used for the investigation of the interaction between π mesons and nucleons. The range of energies over which the photoproduction of μ mesons has been studied is being extended up to 1100 Mev. Besides the production of one π meson, there are also studies of the production of two or three π mesons in a single act.

Studies of the production of π mesons with large momentum transfers have given data on resonances at total energies about 600 and 800 Mev, which are in agreement with the resuls of the analysis of the $\pi-N$ interaction.

The Production of Strange Particles. The study of the strong intraction of strange particles is in an even earlier stage than the study of ordinary particles. Processes of strange-particle production in $\pi-N$ collisions have been studied in the energy range 940-1440 Mev, and processes of photoproduction of strange particles in the energy range 900-1060 Mev.

The cross section for production of a Λ particle in $\pi-N$ collisions reaches a maximum value of $0.8 \cdot 10^{-27}$ cm^2 near 900 Mev and then decreases to $(0.2-0.3) \cdot 10^{-27}$ cm^2 at 1250-1450 Mev. A characteristic feature of strange-particle production is the considerable polarization of the Λ particles. The conservation of isotopic spin and parity in strange-particle production has been verified in special experiments. No violation of these conservation laws was observed.

The Interactions of Strange Particles. The interactions of K^+ and K^- mesons with nucleons and leptons are being studied in the energy range up to 200 Mev. The available data on the total cross sections and the cross section for hyperon production in K—n collisions, and on the angular distributions, allow us to suppose that in this energy range the interaction of K mesons with nucleons is mainly in the s state. The interaction of K mesons with nucleons depends strongly on the value of the isotopic spin. Experiments on the interaction of K mesons with deuterons have confirmed the conservation of isotopic spin in these reactions.

Theorists are concentrating much effort on obtaining information about the interaction of nucleons with hyperons. The analysis of the data on hyperfragments—nuclear systems that contain Λ particles along with nucleons—gives some information about the forces of interaction between hyperons and nucleons. The com-

plete study of this interaction, including the scattering of hyperons by nucleons, is, however, a thing of the future.

Theoretical Advances

In spite of the lack of a theory of the phenomena occurring in collisions of elementary particles which is not self-contradictory, marked successes have been achieved in theoretical physics in the last few years. We have already spoken about the weak interactions. In the domain of the strong interactions the use of the so-called dispersion relations in the analysis of experimental data is very fruitful. Such relations had previously been used successfully for the analysis of optical phenomena in radio engineering. In the case of the interactions of fundamental particles the use of only such general principles as the absence of speeds greater than that of light, the convervation of probability, and so on, makes it possible to establish the analytic properties of the quantities characterizing transition probabilities. The scattering of π mesons by nucleons has been most completely analyzed from the point of view of dispersion relations. The first rigorous proofs of the dispersion relations for $\pi-N$ scattering were given by Symanzik (special case of scattering at angle 0°) and Bogolyubov (more general case of scattering with finite momentum transfer). At present, dispersion relations have been written (through not always proved) for a large number of processes of the scattering of photons, electrons, nucleons, and K mesons by nucleons.

Lehmann has succeeded in determining the analytic properties of the $\pi-N$ scattering amplitude as a function of the momentum transfer. It was this theoretical result that enabled Chew to propose his new method for determining the constant of the reaction from the experimental data.

Since the derivation of the dispersion relations rests only on such general principles as causality, the experimental verification of these relations (especially at high energies) is a matter of the first importance. So far there are no data for such high energies that they can "feel out" distances that are so small that one could doubt that the theory of relativity is still valid. After the 1957 conference it seemed that a case had been found in which the dispersion relations were violated (the scattering of negative π mesons by protons at energies below 150-200 Mev). A more careful analysis, carried out in the past year in various laboratories, showed that there was no basis for this assertion. Much more accurate experimental data will be needed for a reliable comparison of experimental results with the predictions of the dispersion relations.

Various problems in the theory of dispersion relations were discussed at the conference. A new success of the method of dispersion relations was the fact that it was possible with its aid to make a complete analysis of the effects of the strong interaction on the decays of particles.

The Theory of Heisenberg. In all of its forms the present theory operates with such quantities as the mass, spin, parity, and charge of each particle. The values of these quantities are taken from experiment, and they determine the properties of the interaction. For a number of years, Heisenberg has been trying to develop a quite different theory, from which it would be possible to obtain the spectrum of masses of elementary particles and their parities and charges. In such a theory there should be one common equation of matter, just as in ordinary (nonrelativistic) quantum mechanics one does not need separate equations for the oxygen atom, but has a single Schrödinger equation. In his recent papers, Heisenberg has studied the properties of some general equations of this kind. After analyzing these papers the majority of theorists have come to the conclusion that it will be difficult to make a closed theory. At the conference special attention was given to the Heisenberg theory. To say nothing of the lack of adequate foundations for the mathematical methods used by Heisenberg, the commutation relations and equations of motion in his theory were found to be incompatible.

The so-called "indefinite metric" (Dirac, 1942) is an essential part of Heisenberg's new theory. The use of an indefinite metric means that negative probabilities are admitted in intermediate stages of the calculation of probabilities of actual physical processes. The appearance of physically meaningless results is avoided by the imposition of certain supplementary conditions, just as in the present quantum electrodynamics the Lorentz condition allows the introduction of unobservable longitudinal and scalar photons in the intermediate stages of calculations. It was necessary to find an analogous conditions for the indefinite metric. It was shown at the conference (Bogolyubov, Glaser) that all types of the indefinite metric so far considered fail to satisfy the condition of causality. Thus besides purely technical difficulties, the Heisenberg theory contains difficulties of principle that have at present not been overcome.

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START-UP OF A CYCLOTRON WITH A SPATIALLY VARYING MAGNETIC FIELD

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A novel cyclical accelerator, containing a magnetic field which is periodic both in azimuth and radius, was started up in January, 1959 at the Laboratory for Nuclear Problems at the Joint Institute for Nuclear Studies (Dubna). The diameter of the accelerator magnet is 1200 mm. The lines of equal magnetic field intensity form an Archimedes spiral [1] r (cm) = 16.2 φ and the periodicity of the magnetic field configuration is given by N = 6.

The mean value of the magnetic field increases in the radial direction in accordance with the relativistic increase in the mass of the accelerated ion. Since acceleration starts at the center of the magnet, the characteristic frequencies of the free oscillations vary correspondingly from $Q_z = 0$, $Q_r = 1$, (at r = 0) to $Q_z = 0.2$, $Q_r = 0.2$, $Q_r = 1.01$ (at r = 52 cm). The operating point moves in the region of stability without intersecting lines corresponding to resonance frequencies. The single exception is the nonlinear resonance effect at the center of the accelerator ($Q_r = 1$) . This effect was investigated in detail in 1958 in a model; the magnetic field of the model had a periodicity given by N = 4; the radial pitch of this structure was $2\pi\lambda = 8.47$ cm and the lines of equal field formed a spiral characterized by r(cm)= 5.4φ.

It has been shown theoretically that the increase in the mean value of the magnetic field in the radial direction, which is necessary in order to avoid the nonlinear resonance effect at the center of the accelerator, can be smaller if N is increased (N is the order of the nonlinear resonance); this effect is governed by the relation $\frac{N}{2^N(N-1)!}$ With an increase in the radial pitch but a fixed value of N, the relation is $\left(\frac{\lambda_1}{\lambda_2}\right)^{N-2}$.

In view of the fact that the development of the nonlinear resonance effect at $Q_r = 1$ is equivalent to a displacement of the center of the instantaneous orbits with respect to the center of the magnetic field, an investigation has been made of the conditions for vertical stability in displaced orbits. This investigation has shown that the nature of the vertical oscillations is not changed if the deviations of the center of the instantaneous orbits are less than λ. This requirement corresponds to the condition for small deviations from the resonance value for the period of rotation of a particle in the displaced orbit.

The results of this investigation were used as a basis for choosing the parameters in the 6-spiral magnetic-field configuration; with this configuration no nonlinear resonance at the center of the accelerator is observed. The required variation of the magnetic field is obtained by means of iron shims of rectangular cross section. The calculation of the optimum parameters for shims designed to provide the required rough variation of magnetic-field strength was based on the assumption that the shims become magnetized to saturation. The increase in the mean strength of the magnetic field along the radius , corresponding to the requirement for fixed ion-rotation frequency, is obtained by means of thin cylindrical shims which were designed under the assumption that they become uniformly magnetized. In order

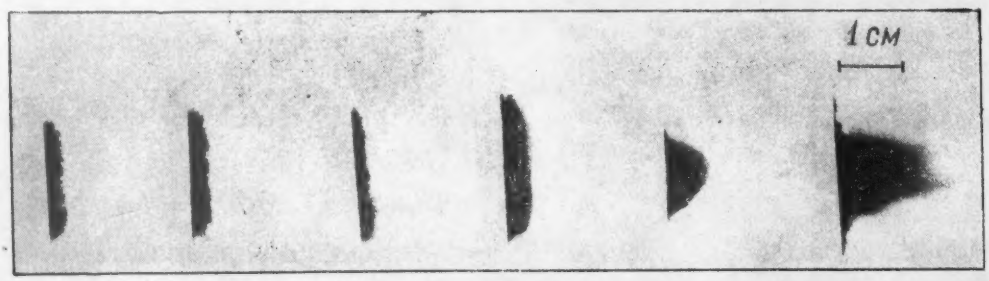

Fig. 1. Autoradiographs of the deuteron beam at various accelerator radii.

to avoid the effects of simple and parametric resonances ($Q_r = 1$), the amplitudes of the first and second harmonics in the magnetic field configuration are reduced by means of symmetrically located cylinders of small diameter (8 mm). All measurements of magnetic-field intensity were carried out with an accuracy of ± 1.5 oe with a nuclear magnetometer [2]. The magnetic field is stabilized by means of a nuclear stabilizer [3].

A quarter-wave resonant system with 1 dee is used for ion acceleration. The resonance system is supplied by an externally excited generator, which provides ac voltages up to 40 kv.

Deuterons have been accelerated to 12 Mev and α particles to 24Mev, with a minimum accelerating voltage of 8 kv at the dee. The energy of the accelerated particles at the terminal radius (52 cm) is measured by two methods: measurement of the mean radius of curvature of the orbit through the use of three probes, and measurement of the range of the accelerated deuterons in aluminum foil.

In order to avoid effects due to any noticeable activity in the construction elements of the chamber, all the measurements were carried out with the intensity of the internal beam kept below 1 μa.

In Fig. 1 are shown autoradiographs of the deuteron beam at various radii. The acceleration chamber of the cyclotron is shown in Fig. 2.

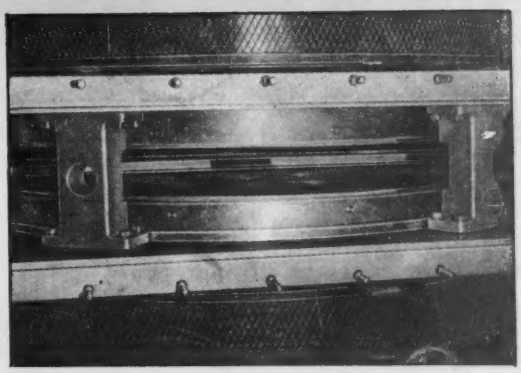

Fig. 2. Acceleration chamber of the cyclotron.

The results of this investigation indicate the possibility of building a relativistic cyclotron with which it should be possible to achieve proton energies in excess of those which can be obtained with present-day synchrocyclotrons (phasotrons).

LITERATURE CITED

1. D. Kerst, K. Terwilliger, K. Symon, and L. Jones, Bull. Am. Phys. Soc. 30, 14 (1955).
2. Yu. N. Denisov, Pribory i Tekh. Éksp. No. 5, 67 (1958).
3. Yu. N. Denisov, Pribory i Tekh. Éksp. No. 1, 96 (1959).

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INDUCTION ACCELERATION OF A BEAM OF CHARGED PARTICLES*

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Attempts to obtain an intense gaseous discharge usually lead to the formation of a plasma current in which the electrons have a relatively small ordered velocity but a large amount of stored energy because of the self-magnetic field. In the present note we present a brief analysis of certain processes by means of which it should be possible to accelerate some of the charged particles or to produce high pulsed-current densities.

We assume that there is a sharp reduction in the directed velocities or the number of electrons of the intense current as a result of some dissipative process (elastic and inelastic collisions with molecules and ions, electron capture, change of conductivity because of a localized change in the electron temperature, application of magnetic fields, etc.). This reduction produces an induction field which accelerates the other particles of the plasma. A rapid reduction in the velocities of peripheral electrons can take place, for example, upon contact of a moving circular discharge with a surface or with a wave front of cold dense gas. The interaction with the surface leads to the ejection of vapors from the surface of the material into the plasma. In order to reduce the amount of such vapor which enters the region occupied by the remaining plasma, it is feasible set up in the current a velocity component along the surface (for example due to the forward motion of a contracting or expanding loop). Because of the rapid tangential motion of the loop it can escape from the region of exploded material vapors; thus it is possible to choose the velocities in such a way as to control the reduction of current and the accumulation of new molecules in a given zone of the discharge.

The ionization of the molecules of the shock from of the material vapors may not lead to shunting of the current if the layer in which electron multiplication takes place is small; this multiplication is a consequence of the small velocities of the electrons and the increased density of the gas, which hinders an increase in the energy of the electrons in this region of the discharge. For acceleration of the electrons which are formed or scattered it is necessary to have a cyclical field which also accelerates the other particles. The production of this induction field is due to the fact that each "micro-

*This work was completed at the end of 1957.

reduction" of the current caused by the loss of electron velocity in an ionization event is not compensated by the remaining electrons which are formed since these move with low velocities.

In the induction transfer of energy in the magnetic field an important role is played by the number of current carriers N per unit length and the linear induction L of the remaining current. From the expression for the total energy of a moving charge characterized by the "classical radius" r_0,

$$W = W_{kin} + W_{mag} = W_{kin}(1 + Nr_0L);$$

it is easy to see that with $Nr_0L \gg 1$, the main part of the energy of motion of a particle is contained in the magnetic field.

If the plasma in the remaining part of the loop contains a sufficiently large number of electrons and if the total magnetic flux through the circuit varies slowly, the peripheral reduction of the conductivity will be accompanied by an increase in the current density in the remaining part of the discharge and an increase in the energy evolved. The sharp increase in the current density leads to an increase in the peripheral intensity of the magnetic field which surrounds the current and intensifies the contraction of the current causing intense heating of the remaining plasma. Because of the short duration of the contraction process the achievable pulse pressures and temperatures may exceed the quasi-static values ($P_{stat} \sim \frac{I^2}{a^2}$, where a(t) is the effective dimension of the cross section of the remaining part of the turn and I is the current strength). At very high current densities, created by a peripheral field $H \gtrsim 3 \cdot 10^6$ oersteds, it is possible for the current to isolate itself because the self-magnetic field repels the diamagnetic molecules of the surrounding medium.

If the conductivity of the plasma is not too large, a reduction in the current can lead to an induction field which is strong enough to make the remaining charges pass through the region of strong momentum loss and energy loss into a region of small loss which is important for further acceleration.† In such a gaseous betatron with an inherent varying magnetic flux the containment of electrons in circular orbits and "vertical" stability may be provided by the Coulomb forces which arise in the disturbance of the quasi-neutral state, or by a combination of the Coulomb forces and the self-magnetic field and/or an external magnetic field. A "skin" distribution of current improves the conditions for separation of the ejected and remaining particle currents. Furthermore, if electrons are accelerated in portions of the discharge, the "material" molecules will have much less effect on these than on the unaccelerated electrons because of the rapid variation in the cross section of the interaction. Both of these circumstances relax their requirements on the density gradients of the material vapor produced by the reduction in current.

It is easy to show that a sharp reduction of current can provide the desired field intensity. $E_{ind} \approx L_{eff}(I_0/\tau)$, where τ is the time required for a sharp reduction of the current in the circuit. For example, with $L_{eff} \approx 5 \cdot 10^{-9}$ h/cm, $I_0 \approx 30$ ka, and $\tau < 10^{-6}$ sec, we find $E_{ind} > 100$ volt/cm, which exceeds the critical field required for acceleration of electrons in a plasma (typical initial electron energies of the order of several electron volts and ion densities of $n \lesssim 10^{14}$ ion/cm^3).

These estimates show that with a sharp reduction in current it is possible to set up conditions which provide continuous acceleration of part of the electrons. The limiting energy required by each of the remaining electrons is $\epsilon_{max} \sim (e/c) L_0 I_0$. For example, for the indicated values of the current and inductance we have $\epsilon_{max} \approx 5$ Mev, i.e., one would expect an enhancement of the hard radiation.

The induction acceleration processes being considered here can also take place in the radial oscillations of an intense discharge; these oscillations lead to cooling of the plasma and the reduction of its conductivity due to expansion or contact with the walls. The strong induction field (of the order of tens of kv/cm, as observed by oscillograms showing current discontinuities of the order of 10^{12} amp/sec) results in continuous accelerations of electrons and ions in a plasma and the appearance of neutron radiation and γ rays [5]. The probability of continuous acceleration of ions is increased as a consequence of the fact that these processes occur in the reduction of the plasma density in the expansion stage in contrast with processes associated with stretching instabilities or with induction redistribution of current and the production of a peripheral conductivity by the self-magnetic field, which increases in contraction). Stretching causes the production of distended regions, which also may cause the current to make contact with the walls. We may note in passing, that the second apperance of current close to the axis of discharge may be due to the induction transfer of current and not to the second contraction of the entire plasma.

It is of interest to study the cosmic versions of the induction acceleration processes being considered here in the currents which circulate in the plasmas of stars and in plasma jets which are projected into cosmic space. These phenomena may be mechanisms for the acceleration of cosmic particles.

LITERATURE CITED

1. R. Giovanelli, Phil. Mag. 40, 206 (1949).
2. G. I. Budker and A. A. Naumov, Proc. CERN Symposium 1, (1957) p. 76.
3. V. I. Veksler, Doklady Akad. Nauk SSSR 118, 263 (1958).

†Various methods of accelerating electrons in a plasma have been considered, for example, in [1-4].

4. H. Dreicer, "On the theory of run-away electrons," Report No. 2292, presented by U.S. at the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).

5. I. V. Kurchatov, Atomnaya Énergiya No. 3, 65 (1956).‡

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‡Original Russian pagination. See C. B. translation.

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"MIXED" ACCELERATORS

E. M. Moroz

In recent years the need for studying interactions of electrons and photons of high energy with matter has become increasingly obvious .

Recently, the present author and V. I. Veksler have indicated the possibility of using the same circular accelerator for alternate or simultaneous acceleration of different particles [1].

Alternate operation of an accelerator does not require any special explanation: the addition to an existing synchrotron (or synchrocyclotron) of an electron injection-acceleration system makes it possible to achieve both electron acceleration and proton acceleration by alternate operation of the two systems.

The use of a single accelerator as a proton accelerator and as an electron accelerator is extremely desirable since these machines are complicated and expensive.

The prospects for mixed acceleration of protons and electrons are still more interesting. (Obviously it is also possible to have simultaneous acceleration of positive ions with different masses. With very good vacuums it may also be possible to accelerate positive and negative ions.)

If it is possible to achieve a significant increase in the the densities of electron beams and proton beams in the accelerator chamber (for which it will be necessary to exploit the attraction of oppositely charged beams moving in opposite directions), it should be possible to achieve a reasonably effective number of collisions between the electron beam and the proton beam .

In this case the velocity v with respect to the laboratory system of the reference system, in which the sum of the momenta of both colliding particles is zero, is given by

$$\frac{v}{c}=\frac{E_p\beta_p-E_e\beta_e}{E_p+E_e}=\frac{r_p-r_e}{\frac{r_p}{\beta_p}+\frac{r_e}{\beta_e}}\ll 1,$$

where E_p and E_e are the total energy of the protons and electrons, respectively, in the laboratory system and $r_p \approx r_e$ are the radii of curvature of the proton trajectory and the electron trajectory.

Thus, the laboratory reference system is essentially the same as the center-of-mass system of the colliding particles. This implies a considerable increase in energy in the mixed accelerator as compared with the cases in which a proton beam collides with a fixed electron target (an increase in the proton energy by a factor of k_p) or an electron beam collides with a fixed proton target (an increase in electron energy by a factor k_e).

Here

$$k_p=\frac{1+\beta_p\beta_e}{\sqrt{1-\beta_e^2}}; \qquad k_e=\frac{1+\beta_p\beta_e}{\sqrt{1-\beta_p}}.$$

In order to realize a mixed accelerator with simultaneous acceleration of beams of particles characterized by different masses it is necessary to overcome a difficulty due to the effect of the field of the electron acceleration resonators on the proton beam.

In the initial acceleration stages the protons rotate much slower than the electrons. Hence, it is necessary to avoid the loss of protons when their rotation period T_p passes through some integral multiple of the electron rotation period T_e. For circular accelerators

$$\frac{\omega_e}{\omega_p}=\frac{T_p}{T_e}\approx\frac{\beta_e}{\beta_p}.$$

The last passage through a "resonance" of this type takes places at an electron energy of several hundred Mev (for low radio-frequency multiplies) at which point the electron energy losses due to radiation are still insignificant.

At electron energies of the order of 3 Bev the frequencies of rotation of the electron beam and the proton beam approach each other and conditions are set up in which it is possible to have a strong perturbation of the proton motion. For this reason it is necessary to find method for eliminating the effect on the proton motion due to very strong (because of the need for compensating the radiation losses) electric field in the electric field in the electron resonator. Obviously the reverse effect, i.e. the effect of the proton acceleration element on the electron motion, is not dangerous because in the initial acceleration period the frequency of the electric field used to accelerate the protons is considerably lower than the electron rotation frequency; later, when the frequencies approach each other, the amplitude of the voltage used to accelerate the protons becomes small compared with the voltage used in the electron accelerator.

There are several methods by which the indicated difficulties can be overcome. In accelerators with weak focusing it is possible to realize a spatial division of the orbits and a corresponding separation of the limiting resonance frequencies of the electron beam and the proton beam; this results is a reduction in the perturbation of the proton orbit. For example, with the frequency difference

$$\Delta\omega = \omega_e - \omega_p$$

the amplitude ΔR_p of the maximum radial perturbation of the proton beam is given by

$$(\Delta R_p)_{max} \approx \frac{1}{\pi}\frac{R}{1-n}\frac{eV_e}{E_p}\frac{\omega_p}{\Delta\omega},$$

where R is the equilibrium radius; n is the magnetic field decay index, and V_e is the voltage used to accelerate the electrons.

The formula which has been given above applies for sizable values of the deviation $\Delta\omega/\omega_p$. In those cases in which the deviation becomes small it is found that synchrotron oscillations of high amplitude are excited; these are associated with the transfer of the protons to a new "equilibrium" orbit which corresponds to the rotational frequency ω_e. Another unfavorable circumstance is the fact that the new "equilibrium" orbit for the protons lies inside the earlier orbit and inside the electron equilibrium orbit (since $\beta_p < \beta_e$); consequently the new orbits approach the inside walls of the vacuum chamber.

The effect of the electron resonators on the proton motion can be suppressed if their perturbation occurs at a frequency which is considerably greater than the electron rotational frequency. However, in accelerators with weak focusing the choice of the allowable frequency multiplication factor is limited by the effects of quantum radiation fluctuations on the amplitude of the electron synchrotron oscillations [2-3]. In accelerators with strong focusing there is no such limitation on the allowable frequency multiplication.

Apparently, the most promising machine is an accelerator in which electrons are accelerated by an electromagnetic wave which travels in the direction of motion of the electrons; it is also possible to make use of systems consisting of two or more resonators located at different azimuths which have a system for adjusting the phase shifts appropriately. Suppose two resonators with the same peak voltage V are excited at the electron rotational frequency with the controlled phase difference

$$\Delta\varphi = \varphi_2 - \varphi_1 = -\frac{\pi}{2}\left(1 - \frac{\Delta\omega}{\omega_p}\right)$$

and are located in two adjacent straight gaps of the racetrack, i.e. at an azimuthal distance $\theta = \pi/2$. The effect of such a system of resonators on the electrons is the same as that of a single resonator with a peak voltage 2V; such a system of resonators neither accelerates nor decelerates the protons, which move in the opposite direction to the motion of the electrons. The control of the phase difference can be small and rather slow because of the slow change in rotational frequency of the protons at relativistic energies.

A simultaneous mixed accelerator for protons and electrons is apparently possible for energies up to several Bev.

LITERATURE CITED

1. V. I. Veksler and E. M. Moroz, Authors Certificate for Patent No. 111367, April 29, 1957.
2. E. M. Moroz, Zhur. Éksp. i Teor. Fiz. 33, 1309(1957).
3. E. M. Moroz, and M. S. Rabinovich, Atomnaya Énergiya 4, 128 (1958).*

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INVESTIGATION OF THE DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING OF 19.6 Mev PROTONS ON SEPARATED ISOTOPES

R. A. Vanetsian, A. P. Klyucharev, and E. D. Fedchenko

A number of authors [1,2] have investigated elastic scattering of nucleons on nuclei with the purpose of obtaining the values of the parameters used in various nuclear models.

In the present work we have measured the differential cross section for elastic scattering of 19.6 Mev protons on the isotopes Li^6, Li^7, Co^{59}, Cu^{63}, Cu^{65}, Ge^{73}, Ge^{74}, Cd^{111}, Cd^{113}, Cd^{116}, Sn^{116}, Sn^{117}, Sn^{118}, Sn^{119}, Sn^{120}, Sn^{122}, Sn^{124}, Pb^{207}, Pb^{208}, Bi^{209}, and U^{238}.

The proton source was a 20 Mev linear accelerator. The scattered protons were detected by two photomultipliers with NaI(Tl) crystals.

The absolute magnitude of the cross section for elastic scattering was measured in the angular region 20–160° with an accuracy of ±5%. The relative differential cross section was measured with an accuracy of ±3%.

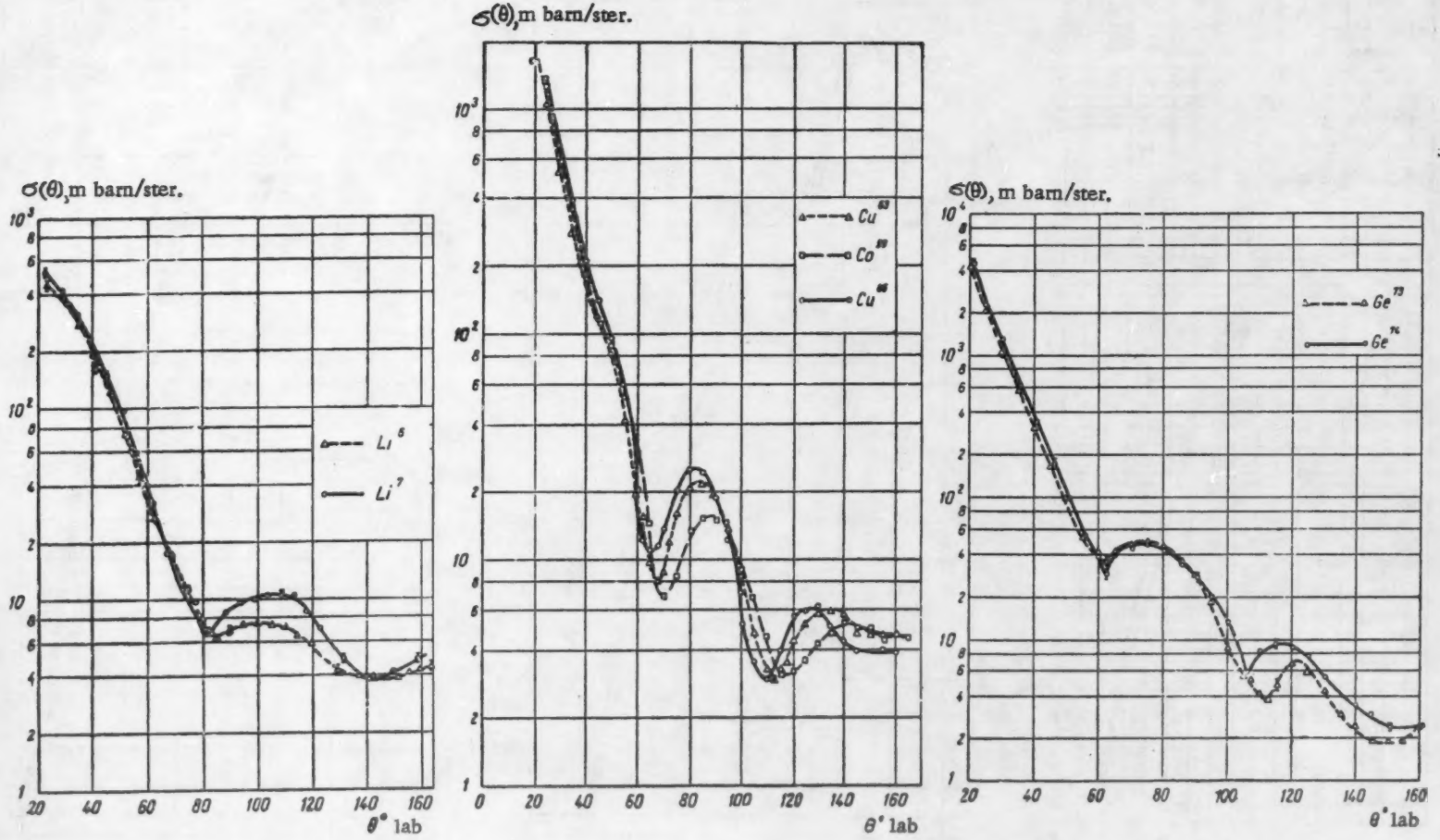
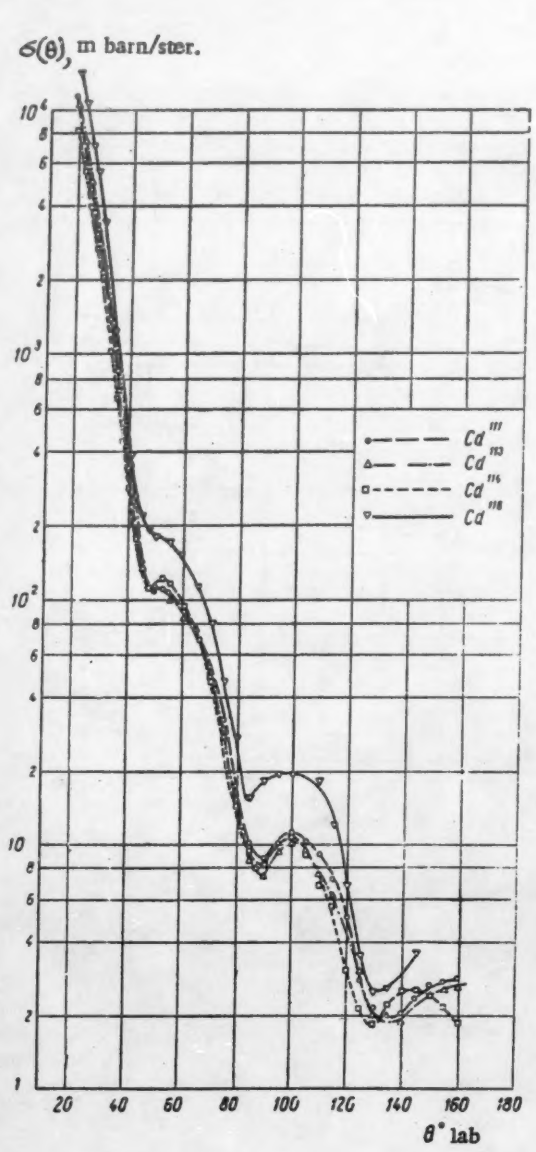
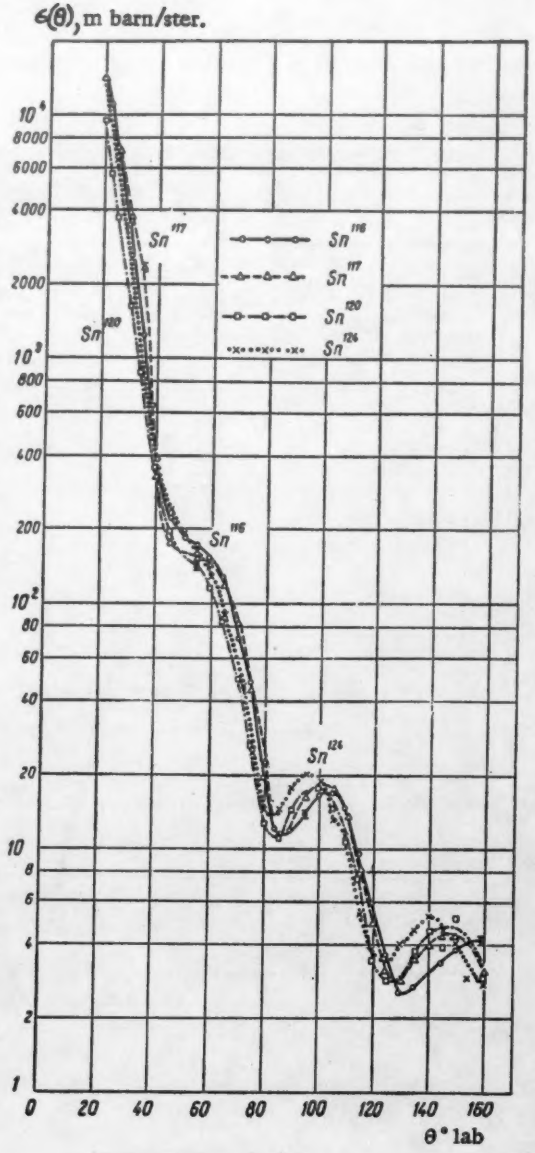
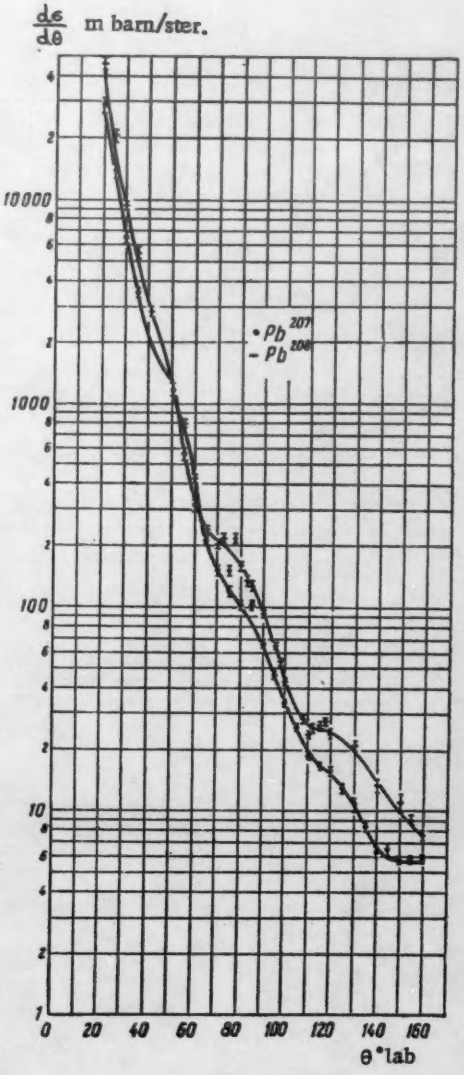


Fig. 1. Differential cross section for elastic scattering of protons with E_{lab} = 19.6 Mev on nuclei.







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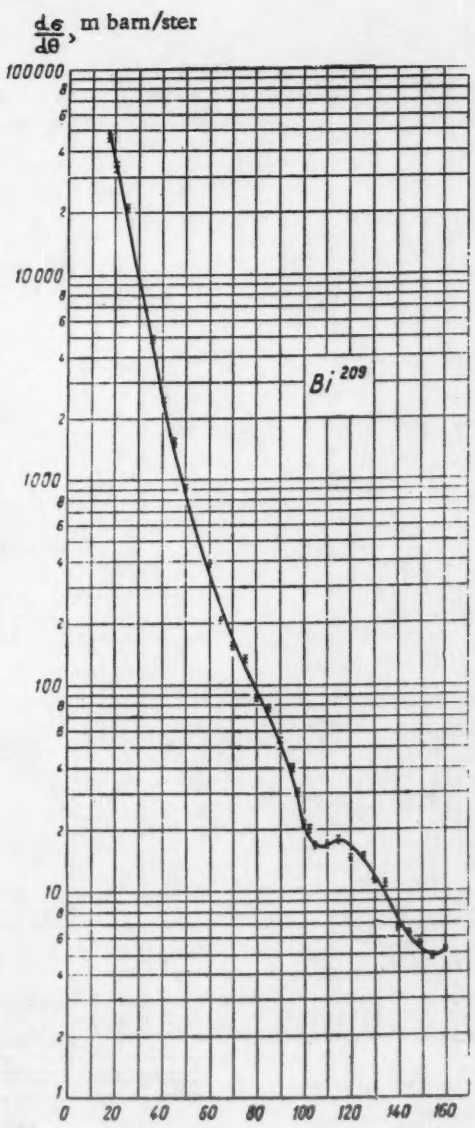

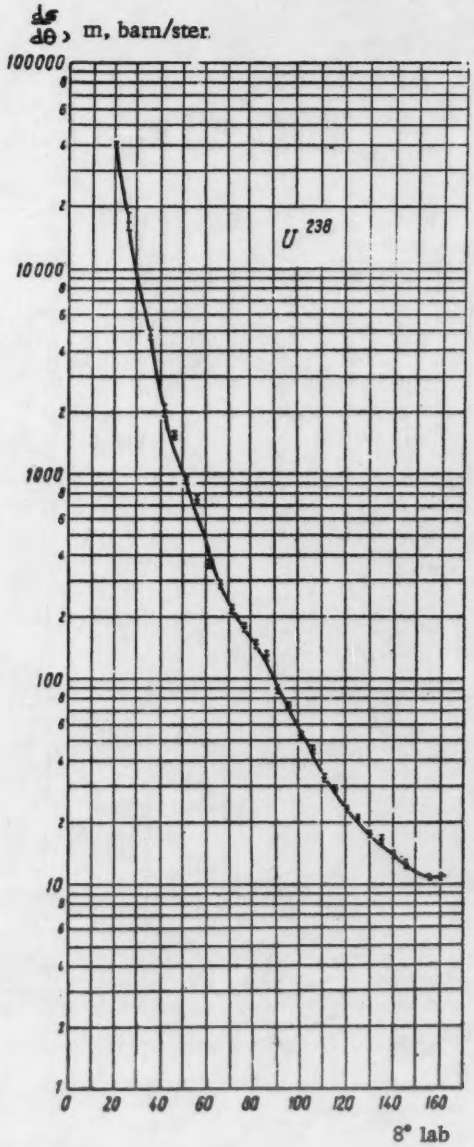

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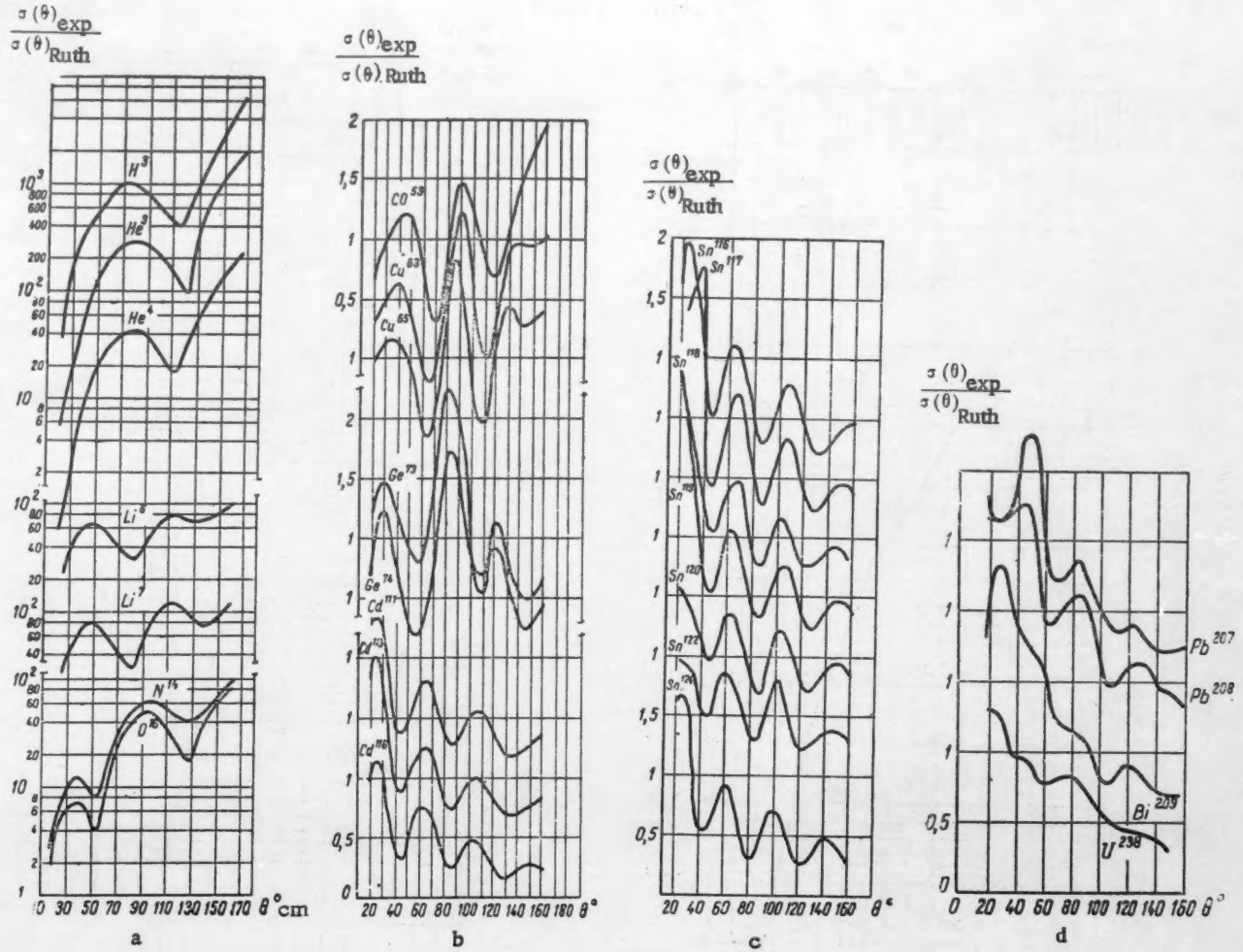

Fig. 2. Ratio of the experimental cross sections for elastic scattering to the Rutherford cross section: a) for light nuclei (the ordinate for He^4 is reduced by a factor of 10); b) for Co^{59}, Cu^{63}, Cu^{65}, Ge^{73}, Ge^{74}, Cd^{111}, Cd^{113}, Cd^{116}; c) for Sn^{116}, Sn^{117}, Sn^{118}, Sn^{119}, Sn^{120}, Sn^{122}, Sn^{124}; d) for Pb^{207}, Pb^{208}, Bi^{209}, U^{238}.

The results of the measurements are shown in Figs. 1 and 2. Figure 1 shows the absolute differential cross sections for elastic scattering; Fig. 2 shows the ratios of the experimental cross sections to the calculated Rutherford cross section.

It is apparent from Fig. 1 that the cross section for forward scattering for both isotopes of lithium is almost the same, whereas the cross section for backward scattering for Li^7 is considerably larger. From Fig. 2a it is apparent that the cross section for Li^6 is much smoother than the cross section for Li^7.

The difference in the behavior of the differential cross sections for elastic scattering in neighboring isotopes or isobars in the region of light nuclei is not especially surprising since the small dimensions of the nuclei limit the number of partial waves which participate in the scattering; thus the effect of a single partial wave can become significant.

The predominance of a given wave depends on the states available to the system. Because the number of states is small, the spin of the target nucleus can have an important effect on the choice of the possible states and, consequently, on the nature of the elastic scattering.

In the heavier nuclei the number of available states becomes so large that the effect of any one partial wave is no longer important. Hence, the difference in the behavior of the elastic scattering cross sections for two neighboring isotopes with different spins may result from the spin dependence of nuclear forces.

Measurements were made of the cross sections for elastic scattering in Ge^{73} and Ge^{74}, which have spins of 9/2 and 0, respectively.

From an analysis of the cross sections for Cu^{63} and Cu^{65} and from the cross section curves for the isotopes of cadmium and tin, it is apparent that the addition of one or more neutrons has almost no effect on the nature of the scattering. The curves for Ge^{73} and Ge^{74} are almost completely identical up to the second minimum and then diverge greatly.

In order to determine whether or not the nuclear spin has an effect on the nature of elastic scattering, measurements were made of the cross sections for Co^{59} and Bi^{209} which have spins of 7/2 and 9/2, respectively. Unfortunately, neither Co^{59} and Bi^{209} has stable isotopes; hence, the cross sections must be compared with the cross sections for nearby nuclei, (for example, Fe, Ni, Cu) which have low spins. No significant discrepancy was noted for Co^{59} as compared with the cross sections for the neighboring nuclei.

From a consideration of the relative behavior of the cross sections for Pb^{207}, Pb^{208}, and Bi^{209}, it is apparent that the Bi^{209} cross section differs significantly (especially in the region of the second maximum) from those for Pb^{207} and Pb^{208}. This difference may be due either to the effect of the extra proton in Pb^{208} (outside the closed shells) or the effect of the high spin.

It may be noted that there is not one case in which the nucleons located outside the closed shells have a strong effect on the scattering. If a comparison is made of the cross sections for elastic proton scattering on He^4 [2] and on Li^6 and Li^7, it is apparent that the addition of two nucleons outside the closed shell of He^4 has a very strong effect on the scattering pattern. There would seem to be a "coupling" of the new angular momenta in the scattering process with the apperance of new nuclear shells.

The behavior of the cross sections for cadmium and tin indicates that the successive adddition of five neutrons to the Cd^{111} nucleus does not change the cross section for elastic scattering whereas the replacement of two neutrons in Cd^{116} by two protons has a considerable effect on the elastic scattering cross section in Sn^{116} as compared with Cd^{116}.

Summarizing the results given above, it may be concluded that while it is still impossible to make an exact estimate of the effect of the various macroscopic nuclear parameters on the nature of the interaction of nucleons with the nucleus, the importance of such factors as spin, proton-neutron ratio, and closing of shells has been established beyond any doubt.

LITERATURE CITED

1. R. LeLevier and D. Saxon, Phys. Rev. 87, 40 (1952); P. Gugelot, Phys. Rev. 87, 525 (1952); B. Cohen and R. Neidigh, Phys. Rev. 93, 282 (1954); F. Rohrlich and D. Chase, Phys. Rev. 94, 81 (1954); B. Kinsey, Phys. Rev. 99, 332 (1955); I. Dayton and G. Schrank, Phys. Rev. 101, 1358 (1956); B. Kinsey and T. Stone, Phys. Rev. 103, 975 (1956); R. Woods and D. Saxon, Phys. Rev. 95, 577 (1954); M. Melkanoff and S. Moszkowski, Phys. Rev. 101, 507 (1956); M. Melkanoff, J. Nodvik, D. Saxon, and R. Woods, Phys. Rev. 106, 793 (1957); N. Hints, Phys. Rev. 106, 1201 (1957); A. Glassgold, W. Cheston, M. Stein, S. Schuldt, and G. Erickson, Phys. Rev. 106, 1207 (1957); A. Glassgold, and P. Kellogg, Phys. Rev. 107, 1372 (1957); W. Waldorf, and N. Wall, Phys. Rev. 107, 1602 (1957); E. Burge, V. Fujimoto, and A. Hossain, Phil. Mag. 1, No. 19 (1956).

2. R. A. Vanetsian and E. D. Fedchenko, Atomnaya Énergiya 2, 123 (1957).*

Received February 16, 1959

*Original Russian pagination. See C. B. translation.

SPATIAL AND ENERGY DISTRIBUTIONS OF NEUTRONS IN BORON CARBIDE

S. P. Belov, V. A. Dulin, Yu. A. Kazanskii,
V. I. Kukhtevich, and S. G. Tsypin

In [1] an investigation has been made of the passage through boron carbide of neutrons from the BR-1 reactor [2]. Since the attenuation of the neutrons depends on the shape of the neutron energy spectrum, it is desirable to know the nature of the attenuation for monoenergetic neutrons.

In the present work an investigation has been made of the spatial and energy distributions of neutrons with energies of 3 and 15 Mev in boron carbide.

The source of 3 Mev neutrons was the reaction $H^2(H^2, n)He^3$; the source of the 15 Mev neutrons was the reaction $H^2(H^3, n)He^4$. The measurements were carried out under conditions of infinite geometry; the source and detector were located in a boron carbide tank with dimensions $1 \times 1 \times 1.5$ m^3. The poured density of the boron carbide was $\gamma = 1.18 \pm 0.05$ g/cm^3. The neutron detectors were located in channels made from thin-walled aluminum tubing 46 mm in diameter. The channels were located in such a way that the minimum number of channels was located on the line between the source and detector close to the source.

The following neutron detectors were used:

1) A BF_3 proportional counter enriched with 88% B^{10};

2) Fission chambers with natural uranium, U^{235} (enriched to 75%) and Th^{232};

3) Threshold indicators $P^{31}(n, p)Si^{31}$; $Al^{27}(n, p)Mg^{27}$; $Fe^{56}(n, p)Mn^{56}$; $Sb^{121}(n, 2n)Sb^{120}$; $Cu^{63}(n, 2n)Cu^{62}$ (described in order of increasing thereshold energy E_{thres}) and $In^{115}(n,\gamma)I^{116m}$.

In Fig. 1 are shown the results of the measurements of the passage through boron carbide of neutrons with initial energies of 3 Mev and 15 Mev. The detectors for the 3 Mev neutrons were the fission chambers and the BF_3 counter; the detectors for the 15 Mev neutrons were the fissions chambers, the BF_3 counter, and the threshold indicators. As is apparent from Fig. 1, an increase in the threshold energy of the detector is accompanied by an increase in the slope of the attenuation curves for the neutrons (at distances $R > 40-50$ cm, where the spectrum may be assumed to be established). Thus, with neutron energies of 3 Mev the neutron relaxation length λ* varies from 13 ± 1 cm (for Th^{232} and natural uranium) to 16.0 ± 0.5 cm (for U^{235} and the BF_3 counter), while for neutron energies of 15 Mev the variation is from 21.5 ± 0.5 cm (for Cu^{63}) to 24.5 ± 0.5 cm (for the BF_3 counter). It should be noted that as the threshold energy is increased the scattered radiation (the bend in the curve at the top) is reduced.

It is interesting that in the measurement of the attenuation of 15 Mev neutrons through the use of the $Cu^{63}(n, 2n)Cu^{62}$ indicator with $E_{thres} = 10.9$ Mev, the relaxation length for the source-detector distance $R > 16$ cm is not changed and is approximately the same as the transport length for boron carbide $\lambda_{tr} = 18 \pm 2$ cm (Fig. 1). The mean cosine of the elastic scattering for neutrons is determined by linear interpolation of the data for differential angular scattering of elastically scattered neutrons on carbon and beryllium at an energy $E = 14.7$ Mev [3].

A comparison of the data obtained in the present work with that obtained in [1] indicates that the relaxation lengths determined by the measurements with the Th^{232} fission chamber in boron carbide are approximately the same for an energy of 3 Mev as the BR-1 reactor spectrum ($\lambda_{3Mev} = 13$ cm, $\lambda_{spect} = 14.5$ cm for a boron carbide density $\gamma = 1.18$ g/cm^3).

Threshold detectors were used to determine the relative number of capture events. For this purpose, all detectors were simultaneously activated, first in the boron carbide and then in a monochromatic neutron beam ($E = 15$ Mev).

The relative number of capture events is given in the Table. The error in this quantity is determined basically by the error in the σ_0 cross section.

The relative number of capture events was also determined by means of a single-crystal scintillation γ spectrometer. In this case the indicators were irradiated inside the boron carbide; the quantities being determined do not depend on σ_0 and were determined from the intensity of the γ lines of the decay products in the indicators.

Using the data in the Table it is possible to estimate the energy distribution of the neutrons for different boron carbide thickness (Fig. 2). In this procedure, account is taken of the dependence of the reaction cross section on the neutron energy and the attenuation of the neutrons in

* In computing the quantity γ, the error introduced by the uncertainty in the determination of the boron carbide density has not been taken into account.

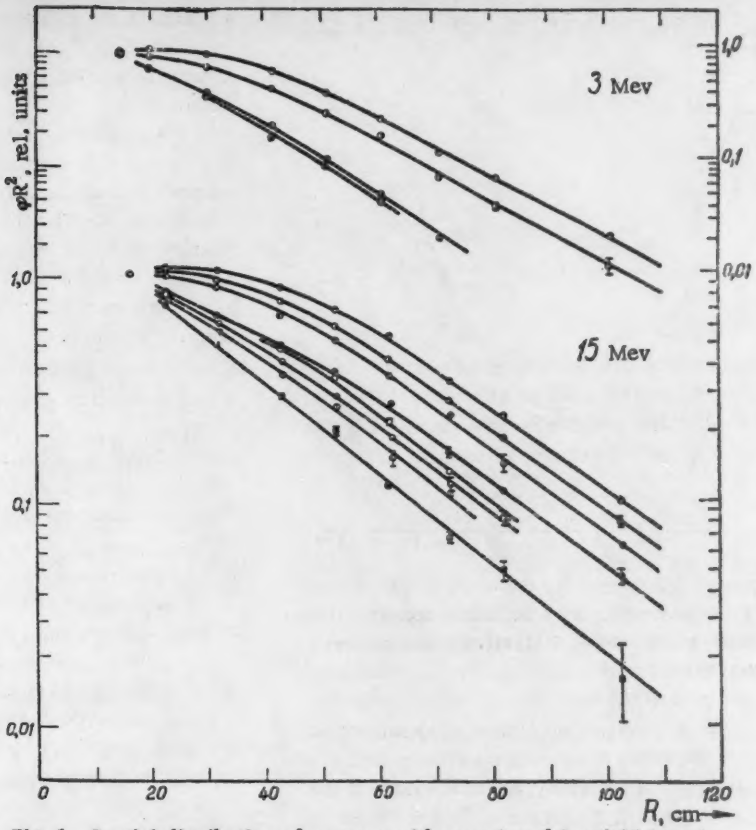

Fig. 1. Spatial distribution of neutrons with energies of 3 and 15 Mev in passage through boron carbide: ◓) BF_3 counter; ◑) U^{235} fission chamber; ◐) $P^{31}(n, p)Si^{31}$; ●) fission chamber with natural unanium (for the 15 Mev case the attenuation curves measured with the Th^{232} fission chambers and the natural uranium chambers were in agreement); ◒) $Al^{27}(n, p)Mg^{27}$; ○) $Fe^{56}(n, p)Mn^{56}$; ⊙) $Sb^{121}(n, 2n)Sb^{120}$; ■) $Cu^{63}(n, 2n)Cu^{62}$; ⊕) Th^{232} fission chamber.

Relative Number of Capture Events

Indicator	Cu^{63}	Sb^{121}	Fe^{56}
Counter measurement	6,5±1	8±2	1
Spectrometer measurement	—	—	1
Indicator	Al^{27}	P^{31}	In^{115}
Counter measurement	0,73±0,15	1,04±0,15	—
Spectrometer measurement	0,65±0,15	—	6±2

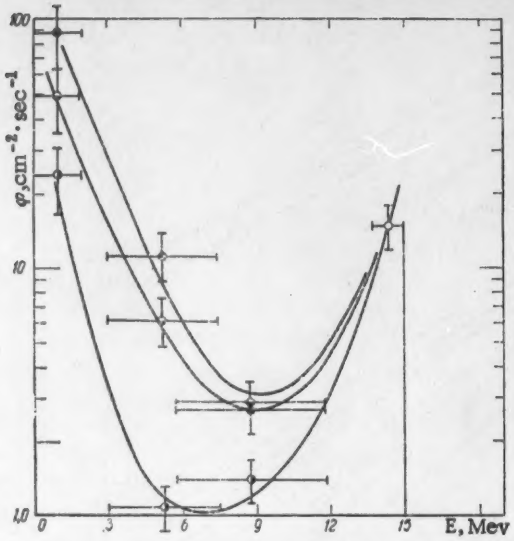

Fig. 2. Energy distribution for the neutron flux in boron carbide at different distance (the results are nomalized in the energy range 13.5–15 Mev): ◑) 16.3 cm; ◒) 40 cm; ●) 70 cm.

boron carbide, as measured by different indicators† (cf. Fig. 1).

A determination was also made of the ratio of the fission cross section $\sigma_{235}(E_{eff})$ for U^{235} to the cross section $\sigma_B(E_{eff})$ for the (n, α) reaction on B^{10} in boron carbide.

This cross section ratio, in the case in which measurements were made of the attenuation of 3 Mev neutrons in the region of the established spectrum, was found to be 0.97 ± 0.03. Using the ratio which was obtained, the effective energy E_{eff} = 120 ± 10 kev was determined.

In conclusion, the authors wish to express their gratitude to I. I. Bondarenko for a number of valuable comments in discussions of the results of the measurements. The authors are also indebted to N. D. Proskurnin, V. F. Vashmakov, A. N. Nikolaev, and V. I. Popov for help in carrying out the experiments, and to A. N. Serbinov and I. A. Voronstsov for providing reliable operation of the neutron generator.

LITERATURE CITED

1. D. L. Broder, S. A. Kurkin, A. A. Kutuzov, V. V. Levin, and V. V. Orlov, "Investigation of the spatial-energy distributions of neutrons in various media," Report No. 2147, presented at the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).
2. A. I. Leipunskii et al., "Physics research in fast-neutron reactors," Report No. 2038 presented at the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).
3. M. Nakada, J. Anderson, C. Gardner, and C. Wong, Phys. Rev. 110, 1439 (1958).
4. D. Hughes and R. Schwartz, Neutron Cross Section (McGraw-Hill, New York, 1958).

Received January 6, 1959

† The relative attenuation measured by In^{115} indicator was essentially the same as the attenuation measured by the P^{31} indicator.

DEVICES FOR MEASURING THE STABLE PERIOD OF NUCLEAR REACTORS

P. I. Popov and E. V. Filipchuk

In this article two devices are described for measuring and recording the stable period of nuclear reactors. These devices were constructed on the basis of logarithmic and potentiometric methods of measuring the steady-state period.

1. The principal circuit of the device for measuring the stable period of a reactor T_r by the logarithmic method is given in Fig. 1a; the circuit is given for supplying power to the filament circuits of tubes T_1, T_2, T_3, and T_4 in Fig. 1b. A 6D4Zh diode (T_1) is used as a logarithmitizing element. In order to extend the range of logarithmitization, dc current is used for the diode cathode filament and the filament circuit is connected to the cathode. The filament voltage of the diode was taken to be 2.7v. The diode transmission coefficient turned out to be $K_1 = 0.15$v for a tenfold change in current ($k_1 = 0.0652$v for a change by a factor of e).

In the first stage of amplification, the tube T_2 (6Zh1Zh) operates in a special state which does not make it possible to obtain a large amplification coefficient (k = 2-3). The anode voltage $U_a = 10$v, first grid voltage $U_{c1} = 1$v, second grid voltage $U_{c2} = 10$v, third grid voltage $U_{c3} = 3.7$v, filament voltage U_f 4v. This state of the tube maintains a large input impedance and, for lowering the noise level, a small grid current.

The second amplification stage is connected to a 6N2P tube. The circuit of the output stage is a differential cathode follower which is resistively coupled to a differential voltage amplifier. The cathode follower and the amplifier are connected, respectively, to two tubes 6N1P and a tube 6N1P. Upon the appearance of a signal at the grid of tube T_5, the grid potential of T_7 changes to the quantity U_1, and the grid potential of tube T_8 to U_2, where U_1 and U_2 have opposite signs. The current I_L in the load R_L of the output stage may be determined from the formula

$$I_L = \frac{R_i R_k}{R_L [R_i + (1+\mu) R_k] + 2 R_i R_k} (U_1 + U_2) s,$$

where R_i, μ, s are parameters of tubes T_7 and T_8; R_L is the load resistance.

The voltages U_1 and U_2 are the result of a voltage amplification UR_g by the corresponding sections of the differential voltage amplifier; therefore, $U_1 = k_4 UR_g$, $U_2 = k_5 UR_g$ (k_4 and k_5 are the amplification coefficients of the sections of the differential voltage amplifier).

For $E_a = 270$ v, $R_L = 6$ ohm, $R_{k4} = R_{k5} = 4.1$ kohm, and effective transconductance $S_{eff} = 50$ ma/v, the output stage maintains a linear characteristic within the bounds -28 ma $\leq I_L \leq +28$ ma and assures high stability for the initial current at the output.

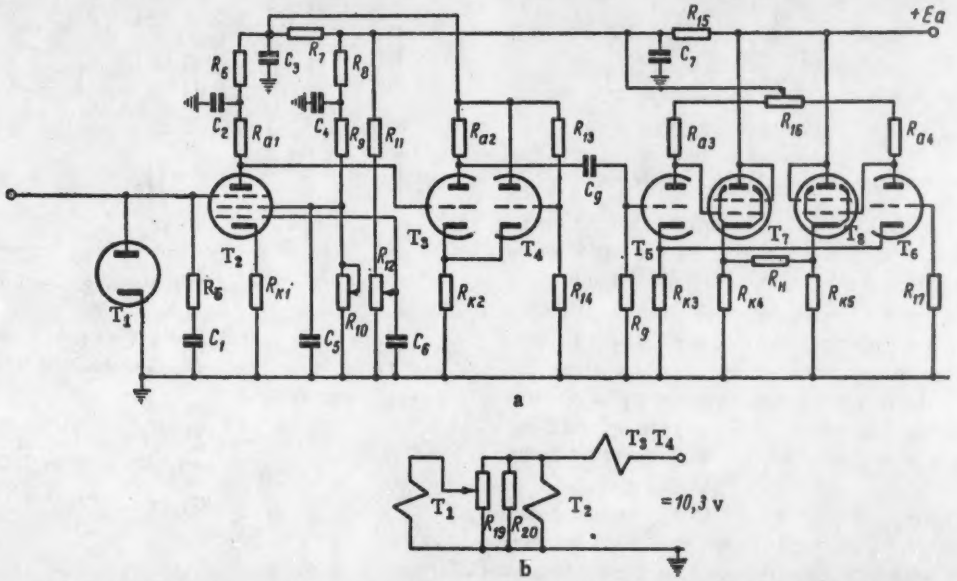

Fig. 1. a) Circuit for measuring the stable period of a reactor by means of the logarithmic method; b) circuit for driving the filament circuits of tubes T_1, T_2, T_3, and T_4.

The static characteristics of the current I_L as a function of $1/T_r$ have a linear character for measurements of T_r in the bounds 2.77-35 sec.

An analysis of the dynamic characteristics indicated that the relative error of measurement ϵ does not exceed 0.03 in this case. It has been established experimentally that the minimum value of current flowing through the diode is $1 \cdot 10^{-8}$ amp. For smaller current values, the e error itself exceeds these values. The range of output indications of the device allows a variation of input current from 10^{-8} to 10^{-3} amp. The sensitivity of the device is approximately 46 ma/sec^{-1}.

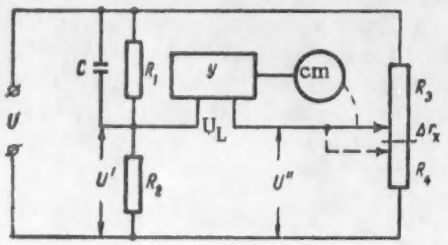

Fig. 2. Measuring circuit.

2. The device for measuring the steady-state period by the potentiometric method is based on the use of the operations of defining the relative rate of growth of the neutron flux by finding its derivative and dividing by the flux.

From the equilibrium condition of the circuit (Fig. 2), upon supplying to it an exponentially varying voltage, it is possible to obtain the relation between the displacement of the slide wire runner and the value of the stable period:

$$x = \frac{\alpha T_1 (1-\alpha)}{T_r + \alpha T_1}, \qquad (1)$$

where $x = \Delta r_x / R$ is the relative displacement of the runner along the slide wire; $\alpha T_1 = \frac{R_1 R_2}{R_1 + R_2} C$ is the time constant of the differentiator, where $\alpha = \frac{R_2}{R_1 + R_2}$.

From the neutron density dependence upon time (after a jump in reactivity) it is evident that the initial value of the relative rate of neutron density variation is much larger than the steady-state value: Therefore, at the initial moment with small αT, the device will indicate values of the inverse period which are much larger than the stable values. This circumstance may give rise to false triggering of a system of emergency protection from the period, if the system is made according to the circuit given.

In order to decrease the error of the measuring device or to exclude false triggering of the emergency protection system, not adversely affecting the dynamic characteristics of the protection system or the device itself, it is convenient to resort to measuring not the stable period of the reactor, but the reactivity ρ. It is possible to compute the reactivity by means of various computing circuits.

The dynamics of a reactor without the temperature coefficient may be described by the following differential equations:

$$\left.\begin{aligned} \frac{dn}{dt} &= \frac{\rho n}{\tau} - \sum_i \frac{dC_i^*}{dt}; \\ \frac{dC_i^*}{dt} &= \frac{\beta n}{\tau} - \lambda_i C_i^*. \end{aligned}\right\} \qquad (2)$$

Here C_i^* is the density of the delayed neutrons, τ is the average life of the neutrons, β_i is the fraction of delayed neutrons in the ith group, n is the density of neutrons in the general number of neutrons emitted in the fission act, λ_i is the decay constant for nuclear radiation in the ith group of delayed neutrons.

From the first equation

$$\rho = \tau \frac{\frac{dn}{dt} + \sum_i \frac{dC_i^*}{dt}}{n}, \qquad (3)$$

that is, to obtain the values of reactivity it is necessary to work out the circuit which produces division by a quantity proportional to

$$\frac{dn}{dt} + \sum_i \frac{dC_i^*}{dt}, \qquad (4)$$

by a quantity proportional to the neutron density. Such an operation for positive values of the reactivity may be performed with aid of the circuit presented in Fig. 3.

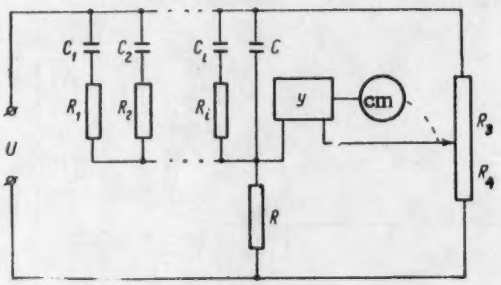

Fig. 3. Circuit for measuring reactivity.

Indeed, if in the circuit given here $R \ll R_1, R_2, \ldots, R_i$ and the RC time constant is less than the life of the prompt neutrons, then

$$U_R = R\left(C\frac{dU}{dt} + C_1\frac{dU_{C1}}{dt} + \ldots + C_i\frac{dU_{Ci}}{dt}\right) = R\left(C\frac{dU}{dt} + \sum_i C_i\frac{dU_{Ci}}{dt}\right)$$

and

$$U = R_i C_i \frac{dU_{Ci}}{dt} + U_{Ci}.$$

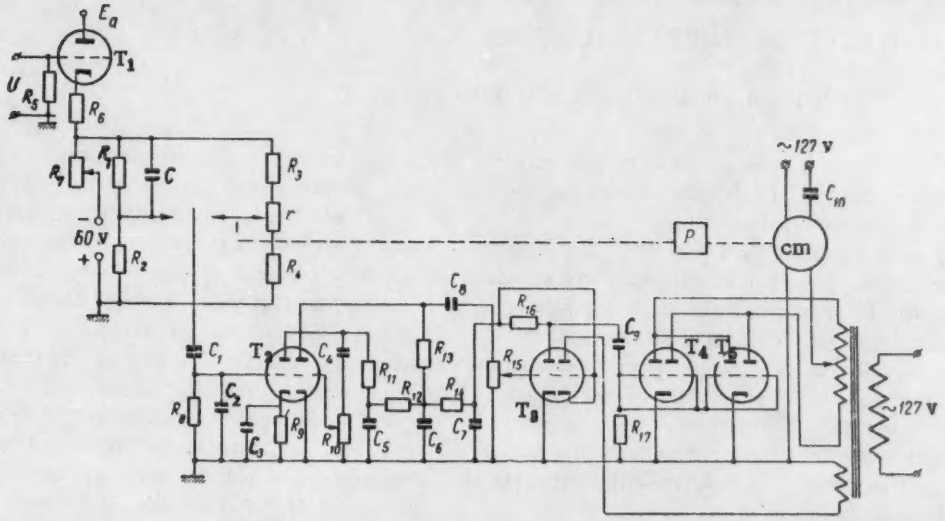

Fig. 4. Circuit for measuring the stable period of reactor by the potentiometric method.

If we take $U=\frac{kn}{C}$, $U_{C_i}=\frac{kC_i^*}{C_i}$, then

$$\frac{kn}{R_iC}=\frac{dC_i^*}{dt}+\frac{C_i^*}{R_iC_i} \qquad (5)$$

and

$$U_R=R\left(\frac{dn}{dt}+\sum_i\frac{dC_i^*}{dt}\right). \qquad (6)$$

If we take $\beta=\frac{k}{R_iC}$, $\lambda_i=\frac{1}{R_iCi}$, then (5) and (6) will be analogous to (2). From the conditions for equilibrium of the circuit we obtain

$$R\left(\frac{dn}{dt}+\sum_i\frac{dC_i^*}{dt}\right)=\frac{kn}{C}x$$

or

$$x=\frac{RC}{k}\,\frac{\frac{dn}{dt}+\sum_i\frac{dC_i^*}{dt}}{n},$$

that is, the displacement of the runner must be proportional to the reactivity. For measuring positive and negative reactivities the capacitor C is shunted by a resistance.

A prototype device for measuring the stable period was built on the basis of autopotentiometer EPP-09. The measuring circuit and potentiometer modulator were designed (Fig. 4). Moreover, a cathode follower input stage was added. The modulator which is used in the autopotentiometer was changed as a consequence of the small input impedance of the autopotentiometer modulator. The modulator developed has input resistance R_g = 0.6 meg, significantly larger than the internal impedance of the measuring circuit. Three stages of amplification at tubes T_2 and $\frac{1}{2}T_3$, rectifier $\frac{1}{2}T_3$, and the output stage of tubes t_4 and T_5, the control motor CM, and the entire kinematic circuit were retained without change.

The circuit devices which have been developed may be used as one of the components in regulating and protecting control devices for reactors.

In comparing properties and characteristics of devices which were constructed using the logarithmic and potentiometric methods, it should be noted that the potentiometer circuits for measuring the period may work in a smaller region of neutron flux variation. Extension of the limits of measuring in this and the other case may be accomplished by including dividers in the input circuit.

The principal defect, which is determined by the principles of constructing the circuits and the elements used, is the substantial inertia of these devices.

LITERATURE CITED

1. E. V. Filipchuk, Coll.: Automation and Remote Control [in Russian] (MIFI, 1958) p. 45.
2. P. I. Popov, ibid. p. 85.
3. S. Glasstone and M. Edlund, The Elements of Nuclear Reactor Theory [Russian translation] (IL, 1954).
4. J. Weill, Nucleonics 3, 36 (1953).

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A NEW SCINTILLATION GEL FOR MEASURING THE ACTIVITY OF SUSPENSIONS*

D. G. Fleishman and L. G. Shakhidzhanyan

The measurement of the activities of samples with the aid of liquid scintillators is finding increasing application in biological investigations.

This method possesses great sensitivity, the ability to resolve ionizing radiations of different energies, and can even provide 4π-geometry for many samples. One of the main advantages of liquid scintillators is the possibility of determining the activity of isotopes with low-energy β particles, which is necessary in working with C^{14}, H^3, S^{35}, and Ca^{45}.

The problem of introducing the sample into the liquid scintillator is met with in connection with making practical use of this method.

In the first stage of the application of liquid scintillator counters, the samples underwent a complicated chemical treatment in order to obtain chemical compounds which are soluble in the liquid scintillator.

The method of introducing the sample in the form of a suspension in the liquid scintillator [1, 2] was proposed in 1955. At the same time, it considerably shortened the time required to prepare the sample. The virtue of this method is the possibility of recovering the sample for further radiation. The method of measuring the activity of suspensions possesses, however, an essential deficiency. The settling of the suspended particles with the course of time changes the geometry of the measurement. This limits the application of the method in measuring weak activities, where very prolonged measuring times are needed to attain the requisite statistical accuracy.

In 1956, work was published concerning the application of scintillation gels in measuring the activity of suspensions. The scintillating gel was obtained by adding stearate of aluminum to ordinary liquid scintillator and heating the colloidal solution obtained to 70°C [3]. The pulse amplitude of the gel obtained was 60% of the pulse amplitude of the original scintillator (in using an external Cs^{137} source). The use of another scintillation gel is described in [4]; here the commercial preparation Thixcin (an organic substance, appearing to be a derivative of castor oil) was used as the gel material.

In order to study samples containing very small quantities of radioactive material, we developed a new scintillation gel. Ordinary plexiglas was used as the gel material. At room temperature plexiglas is slightly soluble in toluene; however, if one adds a shaving of plexiglas to the liquid scintillator (4g/liter p-terphenyl and 0.1 g/liter POPOP in toluene), and heats the mixture obtained to a temperature of approximatly 100°C, then a good scintillation gel will be formed in a few minutes. The quantity of plexiglas added to the original liquid scintillator can be varied within a wide range to obtain gels of various viscosities. A gel with from 5 to 8% by weight of plexiglas appears to be suitable. A gel containing plexiglas possesses a high transparency for the proper radiation. The pulse amplitude measured with an external source (Co^{60}) is 100% of the pulse amplitude of the original liquid scintillator.

The preparation under test is introduced into the gel in the following manner. Dessicated tissue or ash of biological objects is finely pulverized in a mortar and a definite weight of it is poured into a dry glass container. A small amount of liquid scintillator is added to the container to moisten the preparation and the scintillation gel is introduced. After the mixture is stirred vigorously for 1 or 2 minutes, a uniformly distributed suspension of the preparation in the scintillation gel is formed. For a series of measurements of the natural radioactivity of the ash of biological objects, we used a 25 ml container, 100-300 mg of the preparation, 0.5 ml of the liquid scintillator, and 20 ml of the scintillation gel.

By using low noise level FÉU-S and FÉU-1BS photomultipliers, we obtained almost 100% counting efficiency for the β particles of such isotopes as K^{40}, Sr^{90}, and Cs^{137}. The background for this was approximatly 30 counts/min. Data for the natural radioactivity of various human organs which were obtained by the above method have been published [5].

In conclusion, the authors express their deep gratitute to V. V. Glazunov for his help in carrying out the measurements, and to N. S. Khlebnikov for the use of the low noise level photomultiplier.

LITERATURE CITED

1. F. Hayes, A. Anderson, and W. Langham, Application of Liquid Scintillator in Medical Radiology" [Russian translation] (Gostekhizdat, Moscow, 1956).
2. F. Hayes, B. Rogers, and W. Langham, Nucleonics 14, 48 (1956).
3. B. Funt, Nucleonics 14, 83 (1956).
4. C. White and S. Helf, Nucleonics 14, 46 (1956).
5. L. G. Shakhidzhanyan, D. G. Fleishman, V. V. Glazunov, V. G. Leont'ev, and V. P. Nesterov, Doklady Akad. Nauk SSSR 125, No. 1 (1959).

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*This work was reported on at the All-Union Methodical Conference on the Determination of Small Quantities of Radioactive Substances in an External Medium (Leningrad, February, 1958).

A SHIELD FOR SOURCES OF RECTANGULAR-FORM γ RADIATION

D. P. Osanov and E. E. Kovalev

In using sources of γ radiation which are rectangular in form, it is necessary to know the character of the attenuation of the γ radiation in the shield or the surrounding medium.

The existing data on the attenuation of the γ radiation of rectangular sources is incomplete and is only for the cases of the infinite plane [1], and the rectangle of finite width and infinite length [2]. However, the case of the rectangular source of finite dimensions has the most value in solving most practical problems.

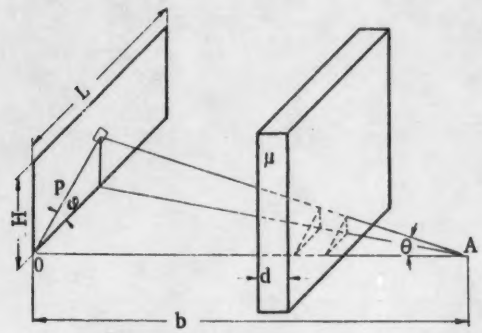

Fig. 1. Attenuation in a shield of the γ radiation from a rectangular source. L and H) dimensions of the source; ρ and φ) present coordinates of the point in the polar system of coordinates with center O.

An investigation is made below of the problem of the attenuation of the γ radiation of a rectangular source of finite dimensions under the following assumptions : 1) the source is an infinitely thin radiating layer; 2) the active material is uniformly distributed over the surface of the source.

The dose rate of the γ radiation at point A at an arbitrary distance b from the plane of the source beyond the shield of thickness d with a coefficient of absorption of the γ radiation μ (Fig. 1) is determined by the expression

$$P = P_\gamma \sigma \int_{(\varphi)} \int_{(\rho)} \frac{d\varphi \rho d\rho}{\rho^2 + b^2} \exp\left(-\mu d \sqrt{\rho^2 + b^2}/b\right), \quad (1)$$

where σ is the surface density of activity; P_γ is the γ decay constant of the radioactive isotope.

In the integration of this expression, one must take into account the fact that the upper limit of the variable ρ depends on φ :

$$P = P_\gamma \sigma \left\{ \int_0^{\operatorname{arctg} n} d\varphi \int_0^{\operatorname{arctg}(m \sec \varphi)} \operatorname{tg} \theta \times \right.$$

$$\times \exp(-\mu d \sec \theta) d\theta +$$

$$\left. + \int_{\operatorname{arctg} n}^{\pi/2} d\varphi \int_0^{\operatorname{arctg}(mn \operatorname{cosec} \varphi)} \operatorname{tg} \theta \exp(-\mu d \sec \theta) d\theta \right\}. \quad (2)$$

Here the substitution b tg θ = ρ was used, and the symbols n = H/L , m = L/b (n characterizes the form of the ractangle, while 1/m is a measure of the relative distance to the given point) have been introduced. On carrying out the internal integration and using the integral exponential function E_i, we obtain the following finite expression :

$$P = P_\gamma \sigma \left\{ \frac{\pi}{2} [-E_i(-\mu d)] - \right.$$

$$- \int_0^{\operatorname{arctg} n} [-E_i(-\mu d \sqrt{1 + m^2 \sec^2 \varphi})] d\varphi -$$

$$\left. - \int_{\operatorname{arctg} n}^{\pi/2} [-E_i(-\mu d \sqrt{1 + m^2 n^2 \operatorname{cosec}^2 \varphi})] d\varphi \right\}. \quad (3)$$

The first term in this expression gives the γ-ray dosage rate from one fourth of the infinite plane; the other two terms contribute to the sum the γ-ray dosage rate from the plane figure which fills up the rectangle to as far as one fourth of the infinite plane.

Formula (3) was used to make a computation of the dosage rate, with a calculation of the attenuation in the shield for the values $0.1 \leq n \leq 1$; $0.02 \leq m \leq 5$, and $1 \leq \mu d \leq 7$. Making the upper limit of the variable n equal to unity does not restrict the generality of the results, since it is always possible to take side L to be the longer side of the rectangle. The results of the calculations for several cases are given in the form of a nomogram in Fig. 2. The value P_0, numerically equal to the dosage rate from a source with unit surface density of activity and unit γ-decay constant, characterizes the influence of the geometrical form of the source on the attenuation of the γ radiation in the shield, and can therefore be termed the geometrical factor for a plane rectangular source.

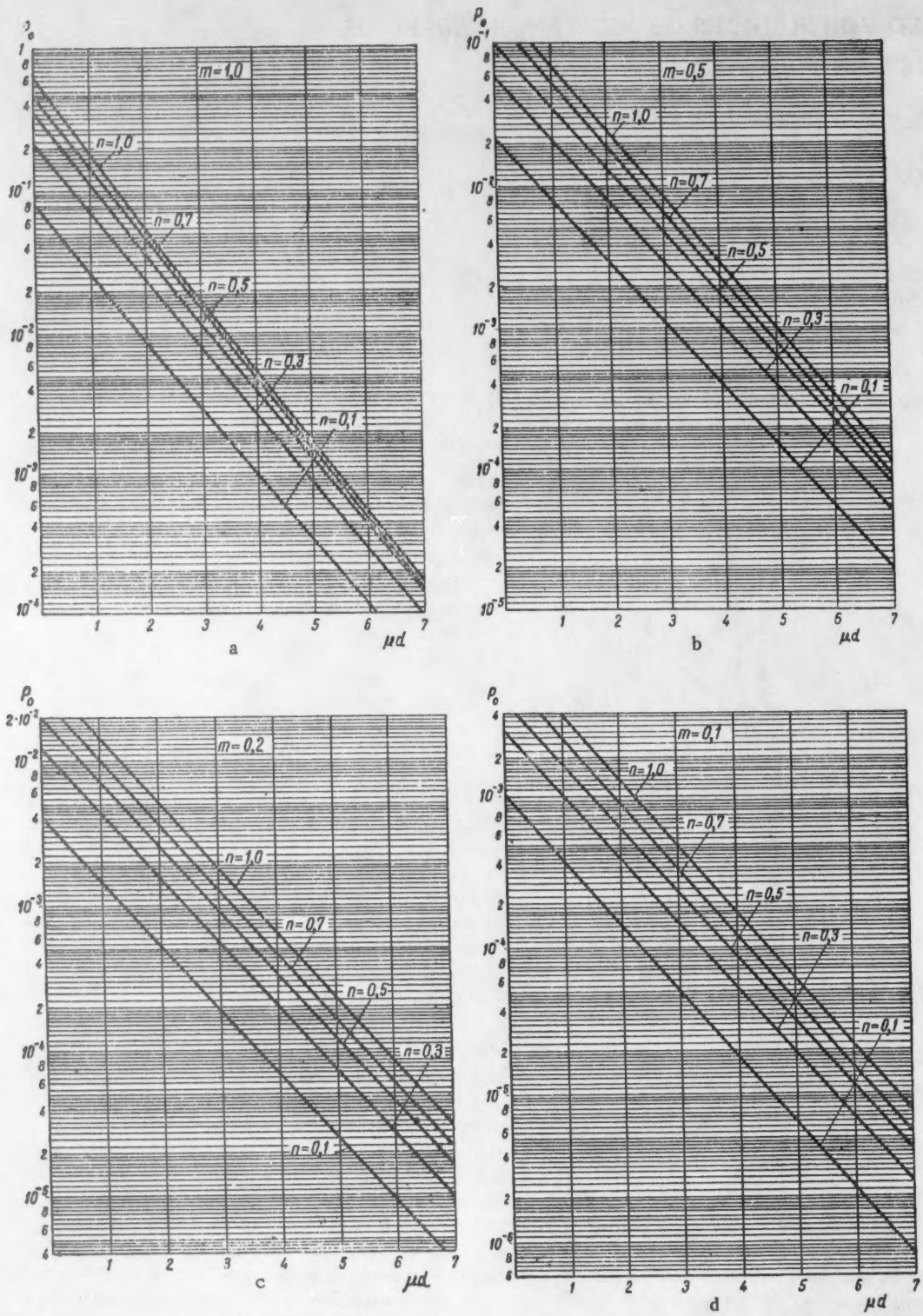

Fig. 2. Nomograms for calculating attenuations in a shield of γ rays from a rectangular source.

Let us give an example to clarify the method of using the nomogran in practical calculations. Let there be given a plane source with sides H = 50 cm, L = 100 cm (n = 0.5), σ = 10 mg-equiv Ra/cm^2 and P_γ = $= 8.4 \frac{\text{r·cm}^2}{\text{mg-equiv Ra·hr}}$. It is required to determine the dosage rate beyond a shielding layer of thickness $\mu d = 3$ at a distance b = 200 cm (m = 0.5) along the perpendicular erected from the vertex of the rectangle (see Fig. 1). According to the nomogram of Fig. 2b, for n = 0.5, m = 0.5, and $\mu d = 3$, we find $P_0 = 4.9 \cdot 10^{-3}$. Thus, $P = P_\gamma \sigma P_0 = 8.4 \times 10 \times 4.9 \cdot 10^{-3} = 0.4$ r/hr. In case the projection of the point for which the dose rate is being calculated does not coincide with any of the vertices of the rectangle, one must use the known rule of the additivity of the dosages of surface sources of γ rays. An example of the use of the this rule for the calculation of a field of γ radiation of rectangular sources has been published [3].

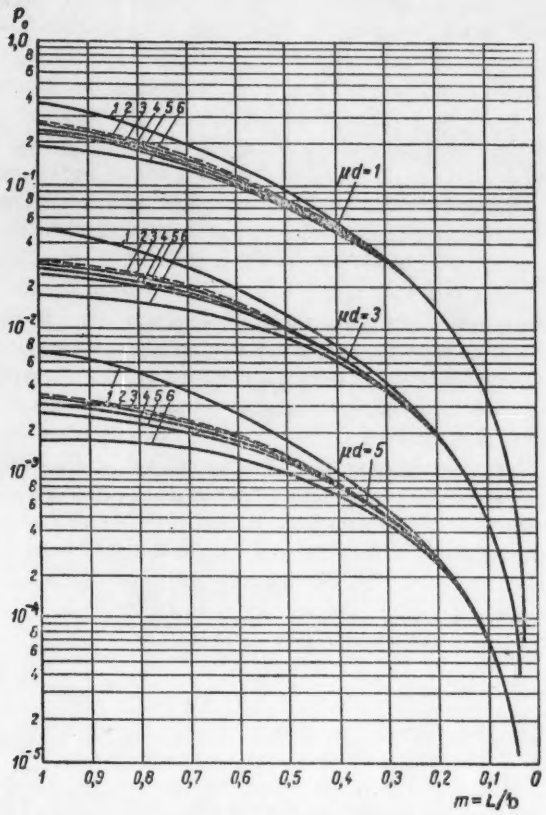

Fig. 3. γ-ray dose rate as a function of distance for various sources: 1) point source; 2) line source; 3) rectangular source, n = 0.1; 4) rectangular source, n = 0.3; 5) rectangular source, n = 0.5; 6) rectangular source, n = 1.0. The different groups of curves correspond to the three different shield thicknesses μd = 1,3, and 5.

The dependence of the dose rate of a rectangular source on distance, for various n and μd is shown by the curves in Fig. 3. The analogous curves for point and line sources are given in the same figure for comparison. In the construction of these curves it was assumed that the total activity of all of the sources (plane rectangles of various dimensions, the line visible from the given point located at the vertex of the rectangle) remains constant. By examining the curves of Fig. 3, one can draw the following conclusions:

1. For large relative distances from the source to the given point ($m \leq 0.05$), it is possible to replace the rectangular source with an arbitrary ratio of sides n by a point source for an arbitrary shield thickness μd.

2. For smaller relative distances, such a replacement is not always possible. Thus, for $m \leq 0.2$ this change will not cause large error for a shield thickness $\mu d \leq 5$; in the case of $m \leq 0.3$, one must have $\mu d \leq 3$, and for $m \leq 0.4$, $\mu d \leq 1$.

3. The rectangular source with a ratio of sides n = 0.1 can in practice be replaced by a line source, for an arbitrary thickness and an arbitrary shield thickness.

The results shown above were obtained without consideration of multiple scattering of the γ rays in the shield. If an analytic representation of the storage factor in the form of a sum of exponentials is made use of, then it is possible to obtain

$$P' = A_1 P(\mu' d,\ m,\ n) + A_2 P(\mu'' d,\ m,\ n), \qquad (4)$$

where $\mu' = \mu(1+\alpha_1)$ and $\mu'' = \mu(1+\alpha_2)$, while the values of A_1, A_2, α_1, and α_2 are listed in [4,5] as a function of γ-ray energy $h\nu$ for various shield thicknesses. The nomograms in Fig. 2 are used to find $P(\mu' d, m, n)$ and $P(\mu'' d, m, n)$.

Strictly speaking, (4) is correct only for the case of a rectangular source immersed in an infinite medium. Such a case may be encountered, for example, in the calculation of deep doses, in the calculation of the dose from a cloud of "rectangular" form [2], etc. In the case of a shield of finite thickness, these results remain correct with accuracy up to the boundary effect.

The effect of multiple scattering in the shield can in many cases be very important. For example, for a rectangular source immersed in water, with m = 0.5, n = 0.5, μd = 3, and γ-ray energy $h\nu = 1$ Mev, the dose rate (with account being taken of multiple scattering) becomes five times as large. At the same time, if this same source is shielded by a lead layer whose thickness μd = 3, the contribution of the multiple scattering of the radiation comprises about 80%.

LITERATURE CITED

1. G. V. Gorshkov, Gamma Radiation of Radioactive Objects [in Russian] (Leningrad State University Press, 1956).

2. P. Lowry, "The theoretical ground-level dose-rate from radioargon emitted by the Brookhaven reactor stack," US AEC report BNL-8 (1950).
3. E. E. Kovalev, V. I. Popov, and L. N. Smirennyi Atomnaya Énergiya 2, 181 (1957).*
4. Reactor Shielding (edited by T. Rockwell) [Russian translation] (IL, 1958).
5. H. Golstein and J. Wilkins, "Calculation of the penetration of λ rays," US AEC report NYO-3075 (1954).

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*Original Russian pagination. See C. B. translation.

INFLUENCE OF BOUNDARY CONDITIONS ON THE BUILD-UP FACTOR OF γ DOSAGES

V. M. Kodyukov

There exists at the present time a sufficiently well-developed theory [1, 2] of the adsorption of the γ rays emitted by a point source placed in an infinite medium. A number of experiments [3-5] have been carried out with sources in an infinite medium. However, in practice one meets with the fundamental case in which the source and detector are separated by a barrier (Fig. 1a). It is therefore of interest to compare the influence of boundary conditions on the build-up factor of the γ-ray dosage. This factor is defined as the ratio of the multiplicity of the attenuation neglecting multiple scattering to the multiplicity of attenuation taking multiple scattering into account. $B = K_0/K$ (in our case $B = e^{\mu_0 x}/K_{exp}$).

The experiments and data of a number of workers [3-5] enable a comparison to be made of the build-up factors among the cases of barrier geometry (source and detector outside the absorbing medium, Fig. 1a), semi-barrier geometry (source in a semiinfinite medium, detector outside it, Fig. 1b), and infinite geometry (source and detector in an infinite medium, Fig. 1c). The radioactive isotopes Au^{198}, Cs^{137}, Zn^{65}, Na^{24} were used as γ-ray sources. The data for these sources is listed in the table.

A metal container, 2 m in height and diameter was used in the experiments. Water was used as the absorbing medium. The dose rate was measured with a specially prepared ionization chamber with air-equivalent walls.

Data for the attenuation of the γ rays of Au^{198} and Na^{24} in water in a semiinfinite medium were taken from the work of V. N. Sakharov [5]. The results of the measurements carried out and the data employed are shown in Fig. 2 in the form of the dependence of K on x. K is the multiplicity of the attenuation ($K = P_0/P_x$), equal to the ratio of the dose rate P at the point of measurement in the absence of water in the container to the dose rate P_x at the same point with water present in the container; x is the thickness of the absorbing medium.

Figure 2 clearly shows the influence of the boundary conditions on the multiplicity of the γ-ray attenuation; it decreases in the case of the semiinfinite medium because of the reflection of the γ-radiation from the layers of water lying below the source, and also in the case of the infinite medium because of the reflection from the layers of water lying below the source and above the detector.

From examining Fig. 2 it is possible to draw the conclusion that the build-up factors of the γ-ray dosages are different for the very same thickness of absorbing material, maximum under the conditions of a infinite medium and minimum for barrier geometry. The difference between the growth factors increases with

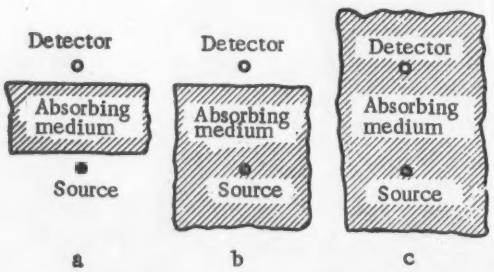


Fig. 1. Geometry of the experiments: a- barriers; b- semibarrier; c-infinite.

Data for the γ-Ray Sources

Isotope	Energy of radiation, Mev	Linear coefficient of absorption in water μ_0, cm^{-1}	$1/\mu_0$, cm
Au^{198}	0,411	0,105	9,5
Cs^{137}	0,661	0,087	11,5
Zn^{65}	1,12	0,068	14,7
Na^{24}	1,38	0,06	16,7
	2,76	0,04	25

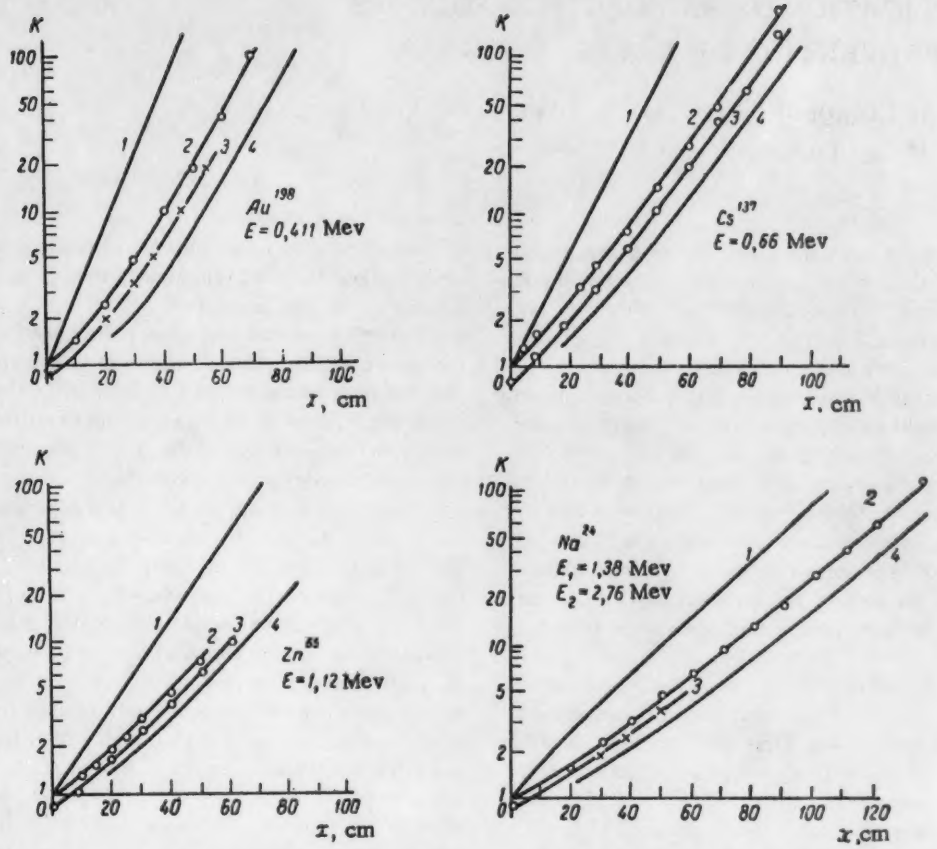


Fig. 2. Curves showing the attenuation of γ-rays from a point source in water; 1) exponential curve; 2) experimental curve of the attenuation for "barrier" geometry; 3) experimental curve for "semibarrier" geometry; 4) calculated curve of the attenuation for "infinite" geometry.

decreasing γ-ray energy. The growth factor under the conditions of a semiinfinite medium has an intermediate value.

LITERATURE CITED

1. L. Spencer and U. Fano, J. Res. Natl. Bur. Standards 46, 2216 (1951).
2. U. Fano, Nucleonics 11, 55 (1953).
3. M. Van Dilla and G. Hine, Nucleonics 10, 54 (1952).
4. S. G. Tsypin, V. I. Kukhtevich, and Yu. A. Kazanskii, Atomnaya Énergiya No. 2, 71 (1956). *
5. V. N. Sakharov, Atomnaya Énergiya 3, 57 (1957). *

*Original Russian pagination. See C. B. translation.

THE APPLICATION OF RADIOACTIVE ISOTOPES TO THE PREVENTION OF MARINE GROWTHS

M. A. Dolgopol'skaya, L. A. Il'in, I. A. Puzanov, and V. A. Tsenev

The purpose of this work is to make an experimental explanation of the possibility of using coverings with radioactive ingredients for protecting ships and other objects from marine growths.*

In order to ensure protection against growths it is necessary to establish a sufficiently high radiation intensity near the surface of the object (within 0—2 mm), in order to kill the larvae of the growths before or soon after their settling on the object. It is clear that β emitters are the most suitable for this purpose. The use of an α emitter is ruled out because of the very low penetrating power of α particles. In the experiments which we carried out, the isotope Y^{91} (dissolved in 3N HCl) was used, whose β particles have a maximum range of ~8 mm in water.

A test of the radioactive coverings in the sea was preceded both by a protracted methodical investigation in regard to the selection of film-forming materials which would enable one to obtain a homogeneous mixture with the available isotope preparation, and by building up of a film of the covering which prevents diffusion of the radioactive substance into the water.

The methods which was worked out consisted in the following. A layer of radioactive solution (a preparation of Y^{91} in a mixture with polyvinylacetate emulsion diluted with water) was built up on the surface of a glass plate 120 · 40 mm and 2.5 mm thick. After heating it up to 60°C and subsequently cooling it to 20°C, the plate surface was covered with three layers of ethinyl lacquer or PKhV-70 lacquer (Fig. 1). The over-all thickness of the covering came to 35 ± 3 mg/cm^2.

The surface activities of plates 1, 2, 3, and 4 are listed in the table.

Identical glass plates covered with polyvinylacetate emulsion and lacquer (ethinyl or PKhV-70), or by only one lacquer, were used as controls.

All of the experimental and control plates were mounted alternately in a staggered fashion 30 cm apart, and immersed to a depth of 1 m in the sea (whose total depth was 3 m) 40 m from shore. The experiments were carried out in the period of the greatest intensity of settling of the larvae of the growths.

The first check was made 10 days after immersion of the plates in the sea. It is evident from Fig. 2 that the growths settled not only on the neutral surface, but also on the applicator. However, the size, density, and character of the deposited individuals were distinctly different from each other. On plate 1, the growths of dimensions up to 2 mm were scattered over the neutral surface (for the most part at a small distance from the applicator); only three fine (less than 1 mm) freshly deposited individuals were discovered on the applicator and near it. On the active surface of plate 2, the quantity of deposited growths was especially large, and, just as in the case of plate 1, their size was much less than the size of the individuals found on the neutral surface.

Other growths besides barnacles among the settled individuals were not recorded. It is probable that in comparison with barnacles they do not possess great sensitivity to radioactivity.

The second check was made 61 days after immersing the plates in the sea. After this period, the control plates and the neutral surface of the experimental plates were covered with a thick layer of barnacles deposited in two or three layers. Over them in separate sections were Razroslis' short pearlweeds, Botrillyusov, calcareous

Variation of the Surface Activity of the Plates

Plates	Active surface area, cm^2	Surface activity, mC/cm^2			
		on the day of putting the plates in the bay, Aug. 6, '57	first check	second check	third check (Nov. 16, 1957)
1	8	0,88	0,78	0,44	0,274
2	8	0,195	0,174	0,098	0,061
3	8	0,146	0,130	0,073	0,046
4	42	$3,3 \cdot 10^{-3}$	$2,9 \cdot 10^{-3}$	$1,65 \cdot 10^{-3}$	$1,03 \cdot 10^{-3}$

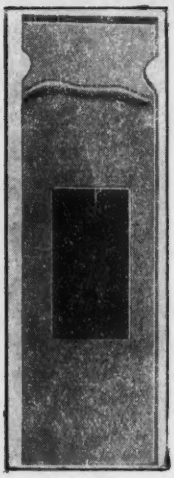


Fig. 1. Over-all view of the experimental plate with applicator before immersion in water.

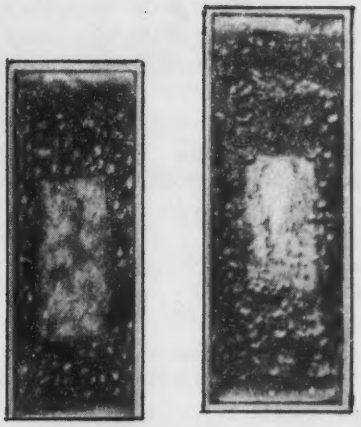
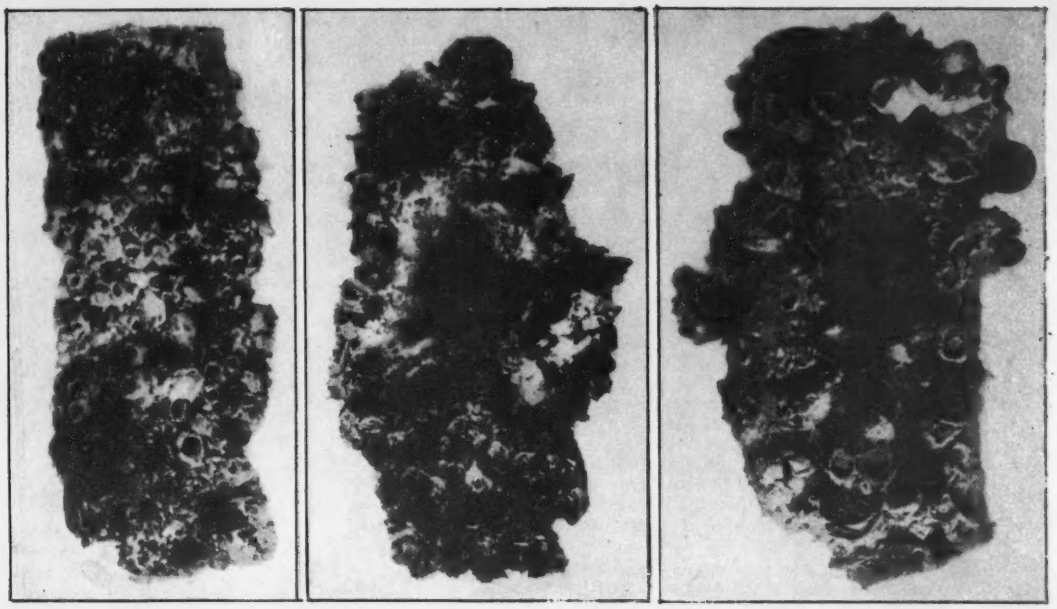


Fig. 2. Plates with applicators 10 days after immersion in the sea: a) plate; b) plate 2.



a b c

Fig. 3. The plates 102 days after immersion in the sea: a) plate 1; b) plate 3; c) control plate.

worm tubes and fine talus of mussels. The total thickness of the layer of growths was as much as 25 mm.

The surface of the applicators of plates 1, 2, and 3 was completely free of growths, except that a layer of growths hung over at some places on the edges at a height of 10-15 mm. The young growths which were noted at the first check on the applicators of plates 1, 2, and 3, were now missing, although the surface activity was only 50% of its initial value. It is evident that the freshly deposited barnacles, not proceeding in becoming securely fastened, were loosened and came off easily. It is necessary to assume that this process took place repeatedly.

The last check was made 102 days after the beginning of the experiment. The surface activity had decreased by a factor of three, but the surface of the applicators of plates 1, 2, and 3 was as before free of growths (see Fig. 3 and the table). The active surface stood out especially sharply on plate 1 and less so on plates 2 and 3. The applicators of plates 1, 2, and 3 were surrounded on all sides by heavy multilayered growths which also covered their remaining inactive surface. Barnacles distributed in several layers made up the bulk of the growths; the diameter of their undersides reached 10-15 mm. After the growth of barnacles was suppressed, creeping forms of pearlweed Razroslis', Kozhistye outgrowths of colonial Ascidi and colonies of mussels grew, the length of which reached 20-22 mm.

The data obtained indicate the possibility in principle of using β-emitting isotopes as a means of prevention of marine growths.

It has been established that with a surface activity of Y^{91} of at least 0.05 mC/cm^2, the overgrowth of objects in the sea does not take place. Very weak activities of the order of $3 \cdot 10^{-3}$ mC/cm^2 (plate 4, see table) stimulate the process of growth of the settling organisms.

It is therefore recommended that in the practical preparation of antiovergrowth coverings, β emitters of a longer lifetime be used than Y^{91}, e.g., Tl^{204} (T = 2.7 years), Ru^{106}–Rh^{106} (T = 360 days), Ce^{144}–Pr^{144} (T= 282 days).

The problem of the practical application of β-active isotopes in preventing marine growths can ultimately be decided only after working out a number of engineering problems and problems of sanitation and hygiene.

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* A means of protection from marine growths by using β-radioactive isotopes was suggested by V. A. Tsenev in 1955.

THE EIGHTH MENDELEEV CONGRESS

March 16-23, 1959 saw the convening in Moscow of the Eighth Mendeleev Congress on General and Applied Chemistry. There were over 2000 participants, including scientists and staffs of industrial enterprises, engineering and technical workers, representatives of chemical training institutes and plant laboratories. Foreign visitors including prominent scientists from 19 countries were also present at the Congress.

Academician A. N. Nesmeyanov, President of the Academy of Sciences, USSR, gave a brief review, in his introductory remarks, of the preceding Mendeleev Congresses, which have always played a great part in bringing together the chemical community of the Soviet Union for the solution of pressing problems in the development of chemical science and industry. Nesmeyanov stressed the fact that the Eighth Mendeleev Congress is devoted to bringing to fruition the resolutions of the Twenty-First Congress of the Communist Party of the Soviet Union pertaining to chemistry: the solution of basic problems in the chemistry and technology of polymers, organic synthesis, chemical kinetics, radiochemistry, biochemistry, metabolism and photochemistry, physical chemistry and electrochemistry, and solutions to chemical problems in the agriculture of the USSR, as well as the problems encountered in the comprehensive utilization of chemical raw materials.

In the concluding portion of his address, Nesmeyanov stressed the point that the Eighth Mendeleev Congress was meeting in the 125th year since the birth of Dmitri Ivanovich Mendeleev, and the 90th year since his discovery of the periodic law governing the chemical elements, which has profoundly altered the entire concept of modern science on the structure of matter.

On the opening day of the Congress, a report was given by Chairman V. S. Fedorov of the State Committee on Chemistry attached to the Council of Ministers of the USSR, on scientific and technical progress in chemical engineering.

The reports by Academicians A. N. Nesmeyanov and N. N. Semenov, posing the most important theoretical problems facing the development of chemical science, were heard with great interest.

In his report entitled "D. I. Mendeleev's periodic system of the elements, and organic chemistry," Academician Nesmeyanov traced the outlines of the pathway of development of the chemistry of heteroorganic compounds, an area in which that scientist has been doing fruitful research for many years. The rapidly developing chemistry of heteroorganic compounds in our country has united the two fundamental branches of chemistry, the organic and inorganic into which chemistry was split up a century and a half ago. Heteroorganic compounds may be used to obtain metals of ultrahigh purity, as well as highly temperature-resistant and oxidation-stable polymers.

Semenov's report, "Basic problems in chemical kinetics," took up new research in the field of free radicals, which are chemically active fragments of molecules. The reporter noted that free radicals play a fundamental role in a very large number of chemical, and possibly biological, reactions. The free radicals play a particularly significant role in chain reactions of such prime importance to industry as cracking, polymerization, oxidation, etc. The theory of the reactivities of radicals was developed in the report, and a program of research was outlined on the major question in modern chemistry, the relationship between the reactivities of chemical substances and their structure.

The report "Fundamental problems in radiochemistry," delivered by Academician A. P. Vinogradov, head of the V. I. Vernadskii Institute of Geochemistry and Analytical Chemistry, stimulated much interest. The radioisotopes manufactured in the use of atomic energy in scientific projects and in the national economy are being widely used for the synthesis and polymerization of organic compounds, as a result of which new substances with technically important properties are being obtained. Vinogradov emphasized the fact that radiochemical techniques have been successfully used in the past few years to discover and isolate the new transuranium elements.

The central events of the panel sessions on radiochemistry and isotope chemistry were the reading of papers by Soviet and American scientists on the discovery of a new artificial element occupying the hundred-and-second place in the periodic table devised by D. I. Mendeleev. This question was discussed in reports by the Soviet Scientist G. N. Flerov, and A. Ghiorso of the University of California. Both the Soviet and American research workers published data, confirming each other's findings, on the existence of element 102.

At the panel sessions on the chemistry and technology of high polymers, a number of reports contained information on the successful application of radiations in the process of producing high polymers. The French chemist Prof. P. Pigagnol delivered an interesting report at this panel on the elaboration of a precision technique for studying the properties of fused polymers.

Reports heard out at the concluding session of the panel were one by Corresponding Member of the Academy of Sciences of the USSR Ya. K. Syrkin, "Basic problems in the theory of the chemical bond," and one by Academician A. P. Aleksandrov, "Chemical aspects of the use of atomic energy."

Aleksandrov characterized perspectives of the utilization of nuclear energy for technological purposes. He stressed the fact that the pathway lying ahead for

the direct chemical utilization of nuclear radiations may become one of the most profitable, in the utilization of the energy of nuclear fuels. For example, by using the radiation of depleted fuel elements of the atomic electric power station under construction in the Voronezhoblast, one hundred thousand automobile tires may be vulcanized anually. The reporter mentioned the innumerable aspects of chemical production in which the energy from radiations may be put to good use, and pointed out the broad range of possibilities open to the new branch of science, radiation chemistry. He stressed particularly the fact that radiation chemistry provides the possibility of manufacturing products with completely new properties, which would be impossible or at least highly difficult to manufacture by conventional means. Much significance is being attached to radiation chemistry in the Soviet Union. Several institutes are engaged in research on radiation chemistry in cobalt facilities, accelerators,and reactors.

Problems concerning chemical engineering and industrial chemistry, chemical equipment,and chemical processing machinery were discussed at the Congress. Problems involving the training of scientific cadres required to bring to realization the sweeping plan for developing chemical processing industries supporting the national economy were taken up in a special symposium devoted to the tasks of higher chemical and technological training.

In his concluding remarks, Academician Nesmeyanov drew up the balance sheet of the gathering, emphasizing the fact that it was better attended and more representative than the preceding Mendeleev Congresses. The reports by Soviet chemists delivered at the Congress were related to the solution of timely problems in the development of chemical industry. The congress discussed over 1500 original research papers.

B.P.

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THE DISCOVERY OF ELEMENT 102

V. Druin

At the Eighth Mendeleev Congress on General and Applied Chemistry, which met in Moscow in March 1959, Corresponding Member of the Academy of Sciences of the USSR G. N. Flerov, and A. Ghiorso (USA), presented reports on work in synthesizing element 102 in the Mendeleev periodic table.

It is common knowledge that the first report on isolation of the new element appeared in the press in 1957. A team of scientists from the USA, Britain,and Sweden reported that experiments they had conducted in Stockholm, bombarding Cm^{244} with C^{13} ions accelerated in a cyclotron, resulted in the successful isolation, chemically, of an isotope of element 102 (presumably 102^{253}). According to their data, this nuclide undergoes α decay (with a half life of 10-15 min), the energy of the α particles amounting to 8.5 Mev.

However, as noted in the reports, the poor reproducibility of the results and the discrepancy between the rather considerable lifetime of the element and the high energy of the α particle was astonishing .

As A. Ghiorso indicated in his report, an opportunity was provided to check the results of the Stockholm experiments, when the linear heavy-ion accelerator at Berkeley went into service. The experiments in the USA were set up under conditions similar to the Swedish experiments. After painstaking, but unsuccessful attempts to isolate the isotope of element 102 having the properties enumerated above, the American scientists, working under the supervision of G. Seaborg and A. Ghiorso, reached the conclusion that the findings of the Stockholm group were spurious.

G. N. Flerov reported on research work carried out in the USSR to obtain element 102. Experiment in that direction were initiated as early as 1956 and were continued until the end of 1958. Those experiments were conducted by a large team of physicists and chemists of the Insitute of Atomic Energy of the Academy of Sciences of the USSR, with the participation of co-workers, in the Joint Institute for Nuclear Studies and the V. I. Vernadskii Institute of Geochemistry and Analytical Chemistry.

The first successful results in the work were attained during the autumn of 1957. Element 102 was obtained as a result of interactions between O^{16} ions, accelerated in a cyclotron, and Pu^{241} nuclei; the disintegration of the new element was recorded by means of a special sampler and nuclear photographic emulsions. It was found that the nuclide of element 102 which was formed was alpha radioactive,an alpha emitter, the alpha particles having energies of approximately 8.8 Mev. The half life of the nuclide obtained fell within the range of several seconds to one minute. The mass number tentatively assigned to the synthesized nuclide is 253. No long-lived activity attributable to element 102 was detected in the course of the experiments.

As A. Ghiorso noted in his report, the totality of the experiments performed at Berkeley and Moscow failed to confirm the findings reported by the Stockholm team.

A.Ghiorsc based his results on the research of the Berkeley group (G. Seaborg, A. Ghiorso et al.) on the synthesis of element 102, in his report. By bombarding Cm^{246} with C^{12} ions, short-lived nuclides of the new element were recorded using a special high-speed device (conveyor belts). In the first experiments on the yield of Fm^{250} , the daughter produced in the decay of element 102, the investigators were successful in measuring the half life of one of the nuclides of element 102, 102^{254} to be specific. It proved to be ~3 sec. In further perfecting the procedure, alphas emitted in the

disintegration of nuclide 102^{254} were recorded, using an ionization chamber. Measurement of the energy of the alpha particles gave the value ~8.3 Mev. Those experiments were carried out in 1958 and in the first months of 1959. A somewhat unexpected result was the observation of fragments of spontaneous fission of 102^{254}. It was discovered in preliminary experiments that the nuclide 102^{254} experiences spontaneous fission in 30% of the cases, in addition to alpha decay, i.e., the period of spontaneous fission is 10^5-10^6 times less than that expected on the basis of the systematics of even-even nuclei.

In the beginning of 1959, an attempt was made to determine the characteristics of the radioactive disintegration ($T_{\frac{1}{2}}$ and E_α) of the nuclide 102^{253} by bombarding Cm^{244} with C^{13} ions. According to preliminary data, the nuclide 102^{253} is characterized by $T_{\frac{1}{2}} \sim$ 15 sec and $E_\alpha \sim$ ~ 8.8 Mev, which shows excellent agreement with the results obtained in the laboratory of G. N. Flerov, from irradiation of Pu^{241} with O^{16} ions.

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THE CYTOGENETIC EFFECT OF SMALL DOSES OF IONIZING RADIATION IN MAMMALS

(An Interview with Yu. Ya. Kerkis, Institute of Cytology and Genetics of the Siberian Division of the Academy of Sciences of the USSR)

V. Parkhit'ko

(Special Correspondent at Novosibirsk)

The question of the effects of small doses of ionizing radiation on the heredity of higher organisms, including the human being, is assuming ever-greater significance. Experimental research carried out during the past several years has established the fact that the genetic effects of radiation have no threshold and that even the most minute doses bring about a certain hereditary effect. For that reason, any increase in the over-all radioactive background of the earth forcefully focuses particular attention on the effects of small doses of ionizing radiation on heredity.

The radiation-genetic sensitivity of different mammals to the same dose of radiation is of considerable interest, not only in understanding the primary mechanism involved in the genetic effect of radiation, but also in developing rational safety measures. The question of the existence of a parallelism between the degree of general sensitivity of the organism to radiation and the sensitivity of the chromosomal apparatus of the organism's reproductive and somatic cells is of particular interest with respect to mammals.

The aim of the research carried out at the laboratory of radiation genetics is to find out the extent of the changes resulting in the chromosomal bodies in response to small doses of x radiation impinging on the sex cells of four species of mammals: the guinea pig, the laboratory rabbit, the white rat, and the white mouse.

Of the total number of changes of different types affecting the hereditary apparatus as a result of irradiation, a significant portion involve rearrangement of the chromosomes. The frequency of chromosomal rearrangements in spermatogonia was used in the experiments as a criterion for the effectiveness of small doses of radiation. The morphological expression of the chromosomal rearrangements was bridges and fragments of chromosomes observed in the anaphases of mitotic processes.

In choosing the dose for irradiation, the laboratory workers were guided by the desirability of establishing the least possible effective dose. Investigations of the cytogenetic effect observable with a dose of 4 r were performed.

The results of the work made it possible to arrive at a conclusion as to the presence of species specificity to the effects of x rays on sex cells in rodents. Of the four species studied, guinea pigs proved to be the most sensitive, followed by white rats, and rabbits. The white mice proved to be the least sensitive to a dose of 4 r.

In guinea pigs, a single radiation dosage of 4 r elicited a large number of chromosomal rearrangements in the gonads: up to 11.4% in the first day following irradiation, compared to 0.83 % in control guinea pigs. In rabbit spermatogonia, the same dose yielded only a slight change in the number of visible rearrangements of chromosomes, which reached 2.1% in the first day following irradiation (0.93% in control rabbits), in rats, 2.42 % (1.48% in control animals), and in mice 0.79% (0.59% in the controls).

Workers of the radiation genetics laboratory of the Institute of Biophysics of the Academy of Sciences of

the USSR, G. G. Tinyakov and M. A. Arsen'eva, detected chromosome rearrangements in the sex cells of monkeys two years after irradiation. Data produced by the Institute of Cytology and Genetics of the Siberian Division of the Academy of Sciences of the USSR demonstrate that damage resulting from irradiation at doses of several roentgens in guinea pigs may be retained over a considerable portion of the period of sexual activity of the animals. According to the findings of Tinyakov and Arsen'eva, the comparative radiosensitivity of the sex cells of primates and mice to doses of 150 and 400 r attests to a higher radiosensitivity on the part of the genetic structures of the monkeys. In monkeys exposed to 400 r, chromosomal rearrangement was observed in 13.94% of the sex cells on the eleventh day following exposure, i.e. approximately the same amount as found, in the laboratory of the Institute, for guinea pigs exposed to a dosage of 4 r (11.4% on the first day following exposure , 10.3% on the third day, and 9.5% on the fifth day). This shows that the cytogenetic radiosensitivity of guinea pigs is many times higher than that of monkeys.

Thus, the existence of such striking differences in the cytogenetic radiosensitivity exhibited by different species of mammals is beyond doubt. It was found that the frequency of rearrangements of chromosomes in guinea pigs exposed to the same dosage of radiation is 50-100 times higher than in rabbits.

All of these data again prove that the cytogenetic effects of radiation depend not only on the amount of the dose, but also on the physiological peculiarities of the exposed organism.

Using the data of Tinyakov and Arsen'eva on the radiation cytogenetics of monkeys, N. P. Dubinin, Director of the Institute of Cytology and Genetics and Corresponding Member of the Academy of Sciences of the USSR, reviewed the question of the dosage of ionizing radiation capable of doubling the frequency of mutations in the human being, a problem of great importance in reaching a precise determination of the genetic effects of a rise in the background of radioactivity on the earth.

The materials resulting from the work in the laboratory of the Institute are highly interesting, since they prove the need to develop further research on detailed study of the radiosensitivity of human hereditary structures. At the present time, one of the possible paths to be pursued in that direction is the qualitative and quantitative analysis of the sequelae of exposure to ionizing radiations in cell nuclei and in human tissue cultures. The laboratory will continue to pursue that avenue of research during 1959.

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BRIEF COMMUNICATIONS

USSR. The Ninth International Conference on High-Energy Physics will meet July 15-25, 1959, in Kiev. 150 delegates from capitalist countries, 65 delegates from the lands of people's democracy, and 85 Soviet delegates will take part in the work of the Conference. In addition, a significant number of Soviet scientists will take part in the work of the Conference in the capacity of observers. Over 18 review papers will be read at the Conference, taking up the most important problems in high-energy physics. The results of experimental and theoretical research conducted by scientists in all countries will be generalized upon and analyzed in those review papers. The Conference is being organized by the International Union of Pure and Applied Physics.

USSR. An International Conference on Cosmic Rays, organized under the auspicies of the International Union of Pure and Applied Physics, will meet July 6-11 , 1959, in Moscow. Over 100 foreign scientists and 400 Soviet scientists will participate in the work of the Conference. About 200 reports will be presented at the Conference.

USSR. At the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958) , some results of experimental research work carried on at the Joint Institute for Nuclear Studies using the synchrocyclotron of the Institute, were reported. Since that time, scientists from twelve countries at work at the Institute have been continuing their research. A working conference took place at the Joint Institute (Dubna) in March , 1959, to discuss the work accomplished.

Participants at the gathering heard and discussed the latest research performed on the synchrocyclotron, using the technique of nuclear photographic emulsions. This research provided interesting data relating to the character of interactions between elementary particles.

USSR. In April, 1959, the Soviet Union was visited by a group of scientists from Columbia University (USA), headed up by Nobel prize winner I. Rabi. During their sojourn in Moscow, the American scientists visited the Joint Institute for Nuclear Studies and other institutions.

USSR. At the Institute of Metal Physics of the Ural branch of the Academy of Sciences of the USSR (in Sverdlovsk), I. G. Fakidov and E. A. Zavadskii designed an installation for producing magnetic fields of unusual intensity . Pulsed magnetic fields with flux densities up to 700 kilogauss were obtained by discharging a bank of capacitors. The utilization factor of the energy stored in the battery of capacitors was raised to 17%. The damping constant of the oscillatory discharge was 4-6, depending on the dimensions of the coil. The

frequency of the oscillations ranged from 3000 to 3500 cps. The coil together with the test sample was placed in ε Dewar flask. When the coils were of large diameter the Dewar was placed directly inside the coils. The axes of the coils were placed both in the vertical and horizontal directions. The coils were made from BRB-2 beryllium bronze and were quenched and aged. A steel ring with a textolite bushing was used to protect the coil from radial expansions. Strong magnetic fields were used to study the magnetoresistance properties of germanium and other semiconductors. Exploitation of the photomagnetoelectric effect in semiconductors is planned. Research into the magnetic and magnetoresistance properties of ferrites and antiferromagnetics will occupy a particularly prominent place in the research.

USSR. In May, 1959, the government of the USSR contributed 500,000 rubles to the fund of the International Atomic Energy Agency, earmarked for technical assistance to member nations of the Agency. The Soviet Union will make available materials and equipment drawable against that sum.

IAEA. In March, 1959, an agreement was reached between Japan and the International Atomic Energy Agency on the delivery to Japan, at a cost of $35.50 per kg, of 3000 kg of natural uranium for the 10 Mw (th) research reactor. This agreement became possible as a result of a gift contribution of natural uranium to the International Agency on the part of Canada.

WEST BERLIN. In mid-March, 1959, the first atomic reactor in the newly inaugurated Institute of Nuclear Chemistry at the University of West Berlin was started up.

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CONCISE "ATOMIC ENERGY" ENCYCLOPEDIA

(Review)

Yu. Koryakin, B. Isaev, M. Shamanov, and G. Zeerev

The State "Great Soviet Encyclopedia" scientific press has published a short "Atomic Energy" encyclopedia*, containing about 1900 terms and definitions. This is the first large-size handbook on atomic energy to appear in the USSR.

It is stated in the editor's foreword that the Encyclopedia is written for a wide readership of Soviet intellectuals. Its aim is to aid the readers in becoming familiar with the outstanding achievements in the field of the applications of atomic energy, and to explain the basic terms used.

On the whole, the concise "Atomic Energy" encyclopedia answers the tasks set out. It not only provides skillful interpretation of many terms and definitions, but also descriptions of the latest achievements in the field of atomic energy at home and abroad. For some applications, the Encyclopedia may be used as a reference handbook by specialists in their respective areas, since it contains a good deal of factual data and information which will prove of use in practical work.

Editions of this kind feature, in addition to brief explanations of terms and definitions, extensive review articles on problem topics. The present Encyclopedia contains such articles under such headings as, e.g.,: "Atomic energy," "Radiation sickness," "Radioactive tracers,",etc. These articles are written on a high scientific level, embrace a broad range of questions, and are at the same time not overlong. Most of the shorter articles are also written on a high scientific level.

On the whole, the edition reviewed here is the result of conscientious and extensive work.

It is all the more disheartening to view then, against the over-all positive background, a rather substantial number of errors, sometimes crude errors. We present below some examples of such errors.

In the article "Dual-purpose reactor," [reaktor dvoinogo naznacheniya] (p. 372), it is stated that this is a "reactor in which the core consists of two zones formed by concentric spheres. The breeding zone is placed at the periphery and the core in the center." Actually, the dual-purpose reactor a designation for a reactor designed for the simultaneous production of plutonium and electric power.† The well-known British Calder Hall type reactors are examples of that type. In addition, the explanation given for the term "two-region reactor" [dvukhzonal'nyi reaktor, p. 119] which is in turn erroneously identified with the term "dual-purpose reactor," is in error. In the first place, the explanation given for the term is illogical, since the first phrase refers to a core consisting of two zones, while the second phrase states that this core consists of a core and a breeding zone. In the second place, it is not clear why the core should necessarily be comprised of two concentric spheres; a two-region reactor may be cylindrical as well, in which case there will be no peripheral breeding zone. In the third place, it is not true that there must necessarily be a breeding zone in a two-region reactor; the concentric zone in the reactor may be formed by a variation in lattice pitch, by the use of different enrichments, or may be due to the fuel geometry, etc.

In defining the term "burnable poison" [vygorayushchii poglotitel'] (p. 85), Xe^{135} is offered as an example. This is incorrect, since Xe^{135} is actually a fission-product poison and is not used as a burnable poison. Boron is commonly employed as a burnable poison (or burnable additive).

There is nothing in the article indicating the function of burnable poisons, so that the definition of the term is inadequate.

On p. 275, the term "steam superheater" is identified with the term "economizer", with the economizer defined as an "apparatus for drying and superheating steam. . .", while on p. 503 the economizer is defined as a "heat exchanger for heating feedwater. . .".

In the article on "Extraction," (p. 509) , it is stated that the distribution coefficient is constant over a broad range of concentrations. This is in error, since the distribution coefficient usually varies rather strongly. Furthermore, it is determined from equilibrium concentrations, and not simply from the concentration, as implied in the article.

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* Kratkaya Éntsiklopediya "Atomnaya Énergiya" ("Bol'shaya Sovetskaya Éntsiklopediya" press, Moscow, 1959). [612 pp., 24 rubles] .

† Translator's note: There is actually no definition given on p. 372; rather, a cross reference is given to "dvukhzonal'nyi reaktor" on p. 119, where the cross reference should have been to an entry for "dvukhtselevoi reaktor" (alternate word for "dual-purpose reactor") on p. 119. The latter is omitted, so that there is no entry in the book for the concept of "dual-purpose reactor." The error on p. 372 is repeated on p. 603.

The statement is made on p. 91 that a galvanometer is designed for measuring ionization currents, whereas it is a familiar fact that the galvanometer is a measurement device of universal application, and its use for measurement of ionization currents happens to be a particular case.

Substantial errors are also encountered in the description of minerals of atomic interest. For example, "gummite" (p. 117) is incorrectly defined as a mixture of curite and soddyite, formed as a result of the breakdown of uraninite alone; "coffinite" (p. 195) is described as a mineral found in sedimentary rocks, whereas actually it also occurs in hydrothermal formations; "pitchblende" (p. 244) is erroneously reported to be an intermediate member of a single series of oxides ranging from uranium blacks to uraninite; "eudialite" $\{(Na, Ca)_6Zr[Si_6O_{17}(O, -OH, Cl)]\}$ (p. 503) is erroneously referred to as a raw material for winning zirconium.

In the article "Uranium occurrences," uraniferous asphaltites (p. 465) are erroneously elevated to the status of a class on equal terms with such subdivisions as sedimentary, magmatogenic, and metamorphogenic deposits.

Errors and inaccuracies of lesser importance are quite in evidence. For example, the explanation of the term "emergency surge tank" (p. 7) is rendered quite categorically. The uninitiated reader may draw the conclusion that this unit is an obligatory component of the heat removal system in any reactor. In reality this is not the case.

We find on p. 16 that the "core of the reactor" is a space in which the liberation of intranuclear energy takes place as the result of a chain reaction. In the first place, it would have been more expedient to use the expression "part of a reactor," rather than the term "space". In the second place, the manner in which the phrase is constructed emphasizes the liberation of energy stored within the nucleus, whereas this is not the paramount feature of the core. Liberation of energy within the nucleus (e.g. gamma radiation emitted by activated nuclei) also takes place in the reflector, as a result of the chain reaction proceeding in the core. A more characteristic feature of the core is that it is the unit in which the chain reaction takes place. Finally, it would have been more correct, in the interests of rigorous scientific definition, to state that fission chain reactions involving heavy-element nuclei are being referred to, since there also exist chemical chain reactions.

It is incorrectly stated on p. 86 that a "high-temperature reactor is a nuclear reactor with a relatively high core temperature (450°C and above). . .". Actually the temperature levels of the fuel, coolant, and moderator are rigidly distinguished from each other in a heterogeneous reactor, and the differences between them may amount to hundreds of degrees. The term "core temperature" is therefore indeterminate.

The term "gas system of the reactor" is not explained clearly. It is stated that this is a device for "removing the gas coolant. . .". A question arises as to whether or not the device feeding-in the gas coolant is to be viewed as an integral part of the gas system.

In the article "Liquid nuclear fuel," (p. 141), it is stated that "aqueous solutions of uranium salts are used as fuel in a boiling-water reactor. . .". Actually, however, solid fuel may also be used in boiling-water reactors, and boiling-water reactors operating on solid fuel are the majority. At the same time, the article "Boiling-water reactor," (p. 182) provides correct information on the fuel used in reactors of this type.

The heading of one long article, "The economics of the atomic raw material industrial," (p. 503), is entirely at variance with its content, since economic problems are not dealt with in the article, rather a description is given of deposits of atomic raw materials and of the development of related processing industries (and then only for capitalist countries). The articles explaining such important entries as "radiation sickness" (p. 321), and "thermal fatigue" (p. 427) contain obsolete concepts; the latter article lacks an adequate explanation of the mechanism involved in thermal fatigue, a subject which has been studied in detail.

There is lacking a critical approach to the use of the "roentgen" as a unit of air dose in modern radiobiology and radiation dosimetry. What should have been provided is a precise and clear-cut concept of the fact that the active biological factor is not the measured dose in air, but the absorbed dose of ionizing radiation. In the article "Integral dose," (p. 163), it is proposed to measure the absorbed dose in gram-roentgens. Aside from the fact that the integral dose is measured in gram-rads in modern radiobiological experiments, the question of just how the dose is determined is left entirely obscure in the article. The question of the absorbed dose is not elucidated in any of the sections dealing with the biological effects of radiation, dosimetry of x radiation or gamma radiation, etc. Further, in the single entry where the "rad" unit is explained, incorrect information is given on the relationship between the "roentgen" and "rad" units.

Actually, for a dose of x radiation or γ radiation in air equal to 1 r in 1 g of tissue, energy equal to 83 erg is absorbed only for a very narrow range of compratively soft radiation ($\sim$ 40 kev), the tissue involved being muscle tissue (the text consistently utilizes the term "tissue" without elaboration). As the hardness of the radiation is increased, the amount of energy absorbed increases and reaches 93-95 erg/g over the most commonly used energy interval. In speaking of the relationship between "roentgen" and "rad" units, it is necessary to specify the particular kind of tissue involved (whether muscle tissue, fatty tissue, bone tissue), since the value of the conversion factor varies greatly in each case; e.g., for bone tissue the relationship between the

roentgen and rad varies several dozen times as the energy of radiation ranges from 20 kev to 1 Mev. The assertion that the "rad" unit has not been adopted officially in the USSR is also at variance with the facts.

The definition of the concept of a tissue-equivalent substance (p. 432) as a substance exhibiting an absorption coefficient for x radiation and gammas equal to the absorption coefficient of the tissue of an animal organism is rendered incorrectly. When applied to the case of neutron radiation, where the chemical composition and not the average atomic number is important, this definition is not reliable.

In the article "Air-equivalent ionization chamber," (p. 81), it is stated that this type of chamber is widely used in medical practice for measuring soft x rays and soft gammas, since the thick walls of the conventional chamber absorb this radiation to a marked degree and introduce errors into the measurements. It is left entirely obscure, just why "thick walls" and "conventional" chambers are involved. The measurements being referred to are also not specified. It is apparent that the author had dose measurements in terms of roentgens in mind, but he failed to state the fact.

The assertion that ionization in a thimble chamber (p. 243) is due principally to the particles arising in the measuring volume, and to a lesser degree due to secondary particles formed in the chamber walls, is not valid. It is well known that the basic ionization effect is caused by particles formed in the chamber walls (i.e. the wall effect) , and not in the measuring volume of the chamber.

In explaining the mechanism of the operation of a non-self-quenching counter (p. 253), it is stated that a burst of a self-sustained discharge propagates throughout the entire working volume of the counter at a speed close to the speed of light. This offers a completely invalid concept of the mechanism involved in its operation. The author of the article obviously had in mind the fact that the excitation of atoms of the gas filling the counter plays a role in the propagation of the discharge within the counter, with subsequent emission of photons of ultraviolet radiation and the ejection of photoelectrons from the counter cathode. The propagation time required for the discharge to propagate throughout the chamber is determined not by the transit time of the photons from their point of origin (at the filament of the counter) to the cathode, but by the time required for the development of the electron avalanche from the cathode to the anode (filament). Usually, the time required for the development of the so-called active stage of the discharge in the counter is a matter of microseconds.

The data on the slope of the counter plateau (cf. "Plateau of counter," p. 292) are unreliable. In modern counters, the slope of the plateau is of the order of 1-2% per 100 v , not 5-10% as stated in the article.

This error is also repeated in the graph of a typical counter characteristic (p. 416) whose slope corresponds imperfectly to that actually recorded for counters now in use.‡

Several inaccuracies are to be found in the description of ionization chambers (p. 165). For example, the assertion that an ionization chamber is a chamber in which two isolated electrodes are present is incorrect.

The assertion that the counter function to "record discrete radioactive particles" (cf. the article "counter," p. 416) is also invalid, since a counter is actually also used to record elementary particles. A long list could be made of similar errors.

The choice of terms honored in the Encyclopedia was not carried out with sufficient discipline, and such strict discipline is necessary with respect to the terminology employed in literature on atomic energy.

As a few examples of nonstandard and dubious terms, we have the "automatic system of emergency protection," [avtomaticheskaya sistema avariinoi zashchity] (p. 8), despite the previous entry of the term "Emergency reactor protection," [avariinaya zashchita reaktora] on p. 7; further: "Nuclear fuel lump," [blok yadernogo topliva**] (p. 66), "Ceramic reactor," †† (p. 180), "Light radiation," [legkoe izluchenie‡‡] (p. 201), "Slurry reactor," [rastvornyi reaktor] (p. 370), "Branched-flow reactor," [Reaktor s razvetvlennym potokom***] (p. 374), "Scram rod," ["stop-sterzhen' " **] (p. 410), and others. Terms such as these only serve to introduce confusion and disharmony into the nomenclature.

At the same time, no entry is provided for the explanation of such terms, fully confirmed by actual practice and tradition, as: "atomic raw materials," [atomnoe syr'e] (while, on p. 503, we have the entry "The economics of the atomic raw materials industry"), "atomic mineral raw materials," [atomnoe mineral'noe syr'e], "atomic raw material data," [atomnye syr'evye materialy], etc., despite the fact that these terms are used in the other articles appearing through the volume.

The absence of any treatment of such important and familiar terms as "radiogeology" and "radiometry" is astounding, particularly in view of the fact that the

‡ Flatness of plateau in graph is far inferior to present standards.

** These terms are simply presented cross referenced to the main term.

†† In reference to a reactor using ceramic components in the core, as moderator or structural element, not necessarily ceramic fuel.

‡‡ Given as "a term used in radiation chemistry to designate ionizing radiations containing a low linear ionization density (gammas, fast electrons)." Light is used as antithesis of "heavy" in the term " light radiation" above.

*** Defined as "a nuclear reactor employing gas coolant, in which the coolant gas is supplied to the center between the cylinder halves comprising the reactor, and then flows in 2 directions from a central header along the channels containing the fuel elements."

bibliography cites the works of V. I. Baranov, "Radiometriya," and of T. V. Voitkevich, "Radiogeologiya."

In describing explorations of radioactive ores, no explanation was provided of the term "geochemical techniques in the exploration of radioactive ores".

A group of terms employed in describing the techonology of atomic raw materials processing escaped the attention of the compilers of the Encyclopedia, e. g. "radiometric enrichment" [radiometricheskoe obogashchenie] and "sorption extraction of uranium" [sorbtsionnoe izvlechenie urana]. Some terms in this group are only partially used in articles on radiochemistry, without due regard to their use in the literature on processing technology.

It is also necessary to point out discrepancies and contradictions between the information offered under different headings, as : "Steam superheater" and "Economizer," "Liquid nuclear fuel," and "Boiling-water reactors," etc. The description of the design and operating principles of atomic and thermonuclear bombs is repeated under four separate headings: "Atomic bomb," (p. 33); "Atomic charge," (p. 49); "Hydrogen bomb," (p. 79); and "Nuclear Weapons," (p. 539); each of the articles enumerated contains drawings showing the design of such bombs.

Notice must be taken of the fact that entirely too much space in the book is given over to military subjects. For example, 16 similar diagrams and photographs of atomic explosions are presented as illustrations to different articles.†††

Finally, the list of recommended literature, containing over 2000 titles of monographs, abstract journals, catalogs, etc., meets with serious objections. Even without examining the list with respect to subject matter, we may state with confidence that the bibliography will be of no practical aid to the reader, since it is very awkwardly arranged for use: it is printed in small print and without paragraphing or identation.

Most of the deficiencies of the Concise "Atomic Energy" Encyclopedia are not due to any absence of experience in publishing books of this nature, but rather apparently to the inadequate qualifications of some of the authors, or else to negligence on the part of the scientific editorial staff. Errors in the publishing stage are particularly misleading to those readers who are not specialists in the field of atomic energy. Such readers are the majority, and they may very likely approach the information offered in the Encyclopedia with complete confidence.

The shortcomings pointed out must be eliminated in subsequent editions of the Encyclopedia.

NEW LITERATURE

NUKLEONIKA (Poland), Vol. IV, No. 1 (1959). This issue contains the following articles: L. Infeld, "Notes on the Second Geneva Conference;" J. Zołowski and M. Zeliński, "The Isotope Effect Observed in the Wet Combustion, Using the Van Slyke Technique, of Several Aliphatic Alcohols and Acids, Tagged with Carbon-14;" A. Selecki, "Separation of Isotopes in Ultracentrifuges;" R. Broszkewicz, "The Use of Ionizing Radiation for Sterilizing Foodstuffs and Drugs;" J. Wasiliuk, "A Review of the Most Important Radioisotopes Used at the Present Time in Biology and Medicine;" K. Kowalska, "Nuclear Research in Brazil;" S. Minc and Z. Libus, "Investigation of the Extractive Properties of Tributylphosphate."

Correspondence: "A 14-Channel Amplitude Analyzer with Detached Scaler;" "An Electronic LE-1 type mod. A. Scaler;" "An Electronic LE-3 type mod. E. Scaler;" "An Electronic LE-4 type Scaler;" "A Detached High-Speed Electronic LE-2 type Scaler;" Book Reviews, News, Bibliography.

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††† Of the approximately 2000 entries, no more than 71 of them deal specifically with atomic weapons, nuclear explosion effects, shielding from fallout contamination, atomic submarines, etc.

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